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UNITED STATES DEPARTMENT OF AGRICULTURE
BULLETIN No. 1059
Contribution from the Forest Service
WILLIAM B. GREELEY, Forester

Washington, D. C. ▼ May 19, 1922

RESEARCH METHODS IN THE STUDY OF FOREST ENVIRONMENT

By

CARLOS G. BATES, Silviculturist
In Charge Fremont Forest Experiment Station
and
RAPHAEL ZON, Forest Economist

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INTRODUCTION.

OBJECT.

Forestry, like engineering or medicine, is largely an applied science. Its development is based on fundamental knowledge of the natural sciences. Knowledge of the tree itself is purely botanical and physiological science. The first contact with its enemies and biotic aids leads into mycology and zoology. Investigation of the effect of environment upon the tree necessarily involves consideration of geology and soils, physics and chemistry, climatology and solar radiation, as well as the biology of the tree's living companions. In measuring the volume and growth of tree and stands, as well as many of the conditions within and without the tree, there is need for mathematics somewhat beyond the elemental. And so on ad infinitum. The present-day forester is keenly alive to the need for help from every possible source of scientific information.

Unfortunately, the investigations undertaken by those trained in forestry must cover so wide a field, and are so often governed by some practical, economic, and immediate necessity, that there is no time or opportunity, and often a lack of the necessary training, for delving into the fundamental problems of the underlying sciences. It is therefore in keeping with the needs of forestry and the spirit of the times to call the attention of scientists in every line to the problems that confront foresters and to seek the cooperation of such scientists in solving them.

While the present bulletin is designed primarily for the aid of forest investigators—those who are giving all of their time to forestry—it is hoped that it will be suggestive to a great many others of problems well worthy of their serious study. An effort must be made to show to such workers the ways in which forestry is weak and as exactly as possible the nature of the problems with which foresters are confronted. To trained scientific workers the discussion of methods with which they are already more than familiar will seem unnecessary. To others familiar with the problems of forestry and perhaps almost overwhelmed by their magnitude it is hoped the same discussions may bring needed suggestions of a technical nature.

A method of investigation is to the scientist what a tool is to a mechanic. The point of view of the investigator, determined by his past experience, knowledge of facts, and philosophy, is to him what manual skill is to the mechanic. The investigator, like the mechanic, to be thoroughly effective, must be able on occasion to make new tools for new and special purposes.

Any suggestion of a handbook, presenting cut-and-dried methods by which research is to be conducted, would be repugnant to the true investigator. The aim of this bulletin must be to clarify the problems so that the investigator may readily choose for himself the method of approach, and not so much to recommend as to enumerate methods and equipment, describing their past accomplishments. If the following discussions do not hold strictly to this point, it should be understood that it is the purpose of this bulletin to build a foundation for the future on the experience of the past, and to suggest the form of the superstructure rather than its architectural design. In this way it is hoped to save the actual designers much needless and fruitless effort.

SCOPE.

In surveying the present field of forest investigations and analyzing the factors which enter into the problems and the methods available for their solution, it appears that, although the number of problems is great and they may vary in character from region to region and from period to period, theoretically they may be conceived as falling into two essential groups. These two groups are (1) ecological and (2) statistical. In solving the ecological problems the aim is to express relations; in solving statistical problems the aim is to express the bare facts of forest growth.

This bulletin will be concerned wholly with ecological forest studies.[1] To some it may seem strange that the word "ecological" should be used rather than the more inclusive "biological." The choice is a question of aims and objectives. "Ecological" better expresses the objects of the knowledge foresters seek to gain. The practice of forestry is in a very large degree the application of ecology. As an example, a forester may be only slightly interested in the abstract physiological fact that trees require sunlight for their development. This fact is taken as a matter of course and allowed for. When, however, he finds that one of two species with which he is dealing requires much more sunlight than the other, or, in other words, does not react so readily to the stimulus of sunlight, the forester then finds a keen interest, because it is a practical interest, in this ecological factor and its relations.

Or, again, the matter may be expressed in this way: The forester, in dealing with a given species, feels that he is dealing with a biological entity whose characters he may know minutely or generally but which he can not change, except possibly through long-term breeding. On the other hand, the environment of this entity can to a considerable degree be controlled, and its reactions to changes in environment can be observed. His concern is therefore not with the physiological functioning of the plant as such, but with its physiological functioning in relation to a given environment.

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[1] The statistical group of problems, in distinction from the ecological, includes chiefly those which deal with the determination of the amount of standing timber, its increment, and other quantitative changes in the stand, with only general reference to the conditions governing, such as might be met in the use of arbitrary site quality classes. As a matter of fact, there can be no sharp line between ecological and statistical forest studies, and as forestry advances there will be a tendency to consider all growth in its ecological relations. It is, however, at the outset necessary to recognize certain standard methods for the measurement of growth, whatever their purpose or use. These methods are distinct from the processes which are ordinarily considered as essential to progress in ecology, and it is for this reason that "measurements," or statistical studies, are not included in the present discussion. The method of determining the growth, volume, and yield of forest stands is largely mechanical, though for sound progress it should, of course, involve knowledge of biology as well as mathematics. The caliper, hypsometer, scaling stick, log scale, increment borer, and tape are practically all the instruments that are required.

Control of environment is the cornerstone of the practice of forestry. The art of the forester is primarily the art of utilizing to best advantage the biological forces active in forest growth, through his ability to modify the environment. Any considerable use of forests means interference with the natural conditions and modification of some of the environmental factors, the sum total of which determined the character of the present forest. Forestry adapts this interference to produce the best results, from the standpoint of human needs. Therefore it has been thought best in this bulletin to take up each of the environmental factors separately, and to introduce only such a discussion of physiological facts as seems necessary to a proper conception of the methods of study of the environment.

Ecological forest studies deal with all problems which involve the determination of the effect of environmental conditions on reproduction, initiation, growth, and physiological functions. To this group belong such studies as the seed production of different species in different seasons and conditions; the characteristics of seeds as related to their origin; the correlation between the composition, succession, and growth of forest vegetation on the one hand, and the conditions of the evironment on the other; the vast field of problems in natural reproduction and methods of cutting for definite silvicultural purposes; the various phases of forestation, including the germination of seed, requirements for shade and water of the different species, the planting of forest trees, and their competition for moisture and light with herbaceous and shrubby vegetation; and many similar problems. The methods and instruments available for the study of the ecological forest problems are essentially the same as those which are used in the study of the physiology and ecology of plants in general. They involve the measurements of such aerial conditions as precipitation, air temperature, the evaporating power of the air, wind velocity and wind direction, and sunshine intensity; and such subterranean conditions as temperature and moisture of the soil, its depth, structure, and chemical composition. The functioning of the tree in response to these conditions must also be measured by the means recognized and used by plant physiologists. The methods and instruments used in physiology, meteorology, and soil physics, therefore, are applicable in a large measure to the study of ecological forest problems, though often with modifications necessitated by the character of the plant and of its environment.

While it is true that in studying the present composition of a forest stand it is necessary, to a certain extent, to have the historical viewpoint in order to determine clearly how this stand was initiated and why it now supports one dominant species rather than another, still it must be recognized that historical studies and conjectures are outside the main domain of ecology. The purpose of ecology as an exact science must always be to measure present conditions and their reactions on the organism, reducing to precise terms relations between environment and life which may be already understood in general terms. In such processes no distinction will be made between a condition which is a direct result of the climate or site, one which is the result of cumulative effects of the presence of the plant formation, and one which may represent the current influence of the present plant formation. Thus, while recognizing in principle and in the application of results historical conditions and the so-called social relations which are particularly important in forest aggregations, it must be clearly understood that, in the current measurements with which this bulletin has to deal, the source of a given condition has no bearing on the method of its determination.

SAMPLE PLOT METHOD COMMON TO BOTH ECOLOGICAL AND STATISTICAL STUDIES.

A method common to both ecological and statistical problems is the method of sample plots. The details of the sample plot method vary with the purpose of the problem which is being investigated. The plot may vary in size from a square foot to an entire section. It may have all possible geometrical forms—circle, square, quadrangle, strip, or triangle. It may be used in the study of herbaceous vegetation, of seedlings in a nursery, or of virgin forests; for the purpose of studying the evolution of the vegetation, for bringing out the effect of a definite condition, for determining the growth of the vegetation, or for observing any other change that takes place in the plant association, whether it be grass, brush, or forest. The principle, however, remains everywhere the same; namely, the use of areas representative of a given type of vegetation for intensive observation over a long period of time.

NEED FOR A PERMANENT ORGANIZATION IN FOREST INVESTIGATIONS.

The great variety of forest stands, the difference between stands in different regions, and the longevity of trees make it difficult for an individual to complete any investigation on the life of the forest. This difficulty is now universally recognized. A permanent organization charged with such investigations has been formed in practically every country in which the care of the forests is a matter of national concern. This permanent organization consists of investigators assigned to forest experiment stations.

FOREST EXPERIMENT STATIONS.

Since it is practically impossible to follow all the changes which take place in a stand during its entire life of 100 years or more, the usual procedure is to carry on a number of observations simultaneously. By distributing the observations over stands of the same character, representing a large number of age gradations, the entire 100-year cycle of development of the stand may be encompassed in 20 years. Even then it often happens that a forest stand, because of an accident, such as fire or insect infestation, may become unsuitable for further observations. It is evident, therefore, that for reliable silvicultural conclusions it is necessary to have under observation a large number of forest stands for long periods of time, and, therefore, a permanent investigative organization, which will insure the completion of long-term experiments and correlate in a systematic and uniform way the observations conducted by many investigators throughout the country. The investigations which come as a general rule distinctly under the work of forest experiment stations are: (1) Forest meteorological observations; (2) distribution of species and types in relation to climate and soils; (3) studies of the growth, volume, and yield of forest stands; (4) studies of the effect of the source of seed upon the resulting forest stand; (5) experiments with the introduction of exotic species; (6) experiments with different silvicultural methods of cutting for the purpose of securing natural reproduction; (7) methods of artificial reproduction; (8) the study of the effect of different methods of thinning upon the growth of the main stand; and (9) studies of the effect of site upon the technical properties of the wood produced. These investigations are beyond the ability of an individual investigator to handle because their solution requires either a very long period of years, often exceeding the life of a single man, or the simultaneous establishment of many experiments in different places—a wholesale method of observations—or expensive apparatus. It is true that some of the problems involved have been studied by individual investigators with very suggestive results, but there is no doubt that forest experiment stations, being less subject to the uncertainties of individual effort, can conduct such studies with greater uniformity and assurance of success.

SHORT-TERM STUDIES.

Although in the study of forest stands the most reliable results will be secured only by permanent, well-equipped experiment stations organized and maintained by the Federal Government, States, or institutions, much can be accomplished also by comparatively short studies of individual investigators.

Studies which do not involve continuous observations for a long period of years or expensive stationary instruments and equipment—for example, microscopic and chemical studies of woods or studies of natural reproduction, distribution, and growth—may be conducted without permanent forest experiment stations; and even observations on climate in its relation to forest vegetation may sometimes be made on short field trips. Very often the painstaking observer, without extensive apparatus, will discover some fundamental facts which alter the conception of a given problem, and which therefore lead to far more productive efforts by the permanent organizations which can study the problem for longer periods. It is only by recognizing this principle of supplemental effort that substantial progress in forest investigations can be made. There should be no attempt to delimit the work of any organization or individual.

THE SIMPLE PHYSICO-PHYSIOLOGICAL CONCEPT.

Many ecological problems are less confusing to the beginner and are more likely to be approached by sound methods if, at the outset, a rather definite physical interpretation of life is accepted, for through such a concept is gained an idea as to the probable physical reaction to the environment and the method of measuring the physical conditions.

Thus, to begin with, the living mass of plants (the protoplasmic mass, primarily) may be conceived to be simply a colloidal mass of organic compounds with a peculiar affinity for water. Water is of fundamental importance to its life qualities. To supply the demand for water, the protoplasmic mass must possess a greater affinity for it than the soil or solution from which the water is to be obtained. The struggle for water is, primarily, a contest between the colloids of the plant and the organic and inorganic (clay) colloids of the soil.

Secondly, it is inevitable that any object possessing water should lose the same by evaporation to the atmosphere until a balance is reached between the vapor pressure of the water-holding mass and that of the atmosphere. Such an equilibrium does not, necessarily, mean death, at least for certain kinds of tissues, but the small supply of water represented by equilibrium with ordinary atmospheric vapor is insufficient to permit photo-synthesis, metabolism, and transport within the plant. For continued functioning, the plant must be able to maintain its water supply above this level.

The objective of physiological functioning is reproduction, to which growth is only incidental. The object in the existence of any individual plant is to extract enough phosphorus[1] from the soil so that a peculiar accumulation of matter called a seed may be formed, with a sufficient affinity for water and a sufficiently close chemical combination to enable this embryonic plant to resist all of the forces of disintegration during a period of dormancy.

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[1] Phosphorus is mentioned only as an example of the vitally necessary elements obtained from the soil.

The first requirement, then, is that the present plant should live long enough to accumulate by absorption from the soil a quantity of phosphorus which may be concentrated in this one seed, or ten thousand seeds, as the case may be.

To accomplish this object, it is rather evident that a large amount of water must be absorbed and disposed of, with a resulting deposit of phosphorus and other solids as the water is evaporated. Even then there must be a strong tendency for such solids, if retained in solution, to diffuse back to the roots and into the soil. Not denying the possible ability of the plant to trap and hold phosphorus, or any other needed substance, at the point where needed, it seems necessary to call into play some other physical force to effect this concentration. The only other possible force is the electromagnetic affinity of energy for matter and of matter for energy. The ability of the plant to concentrate the essential inorganic substances in the best-lighted parts of its structure may thus be explained.

In other words, the requirement of plants for light is primarily a requirement for a concentration of essential substances needed for reproduction. But light can only be obtained where there is competition through growth. To insure the necessary amount of light, the individual plant is required to keep its head at least up to the level of the competitors, and the plant which becomes dominant is most certain to reproduce. Possible differences between plants, in their ability to make use of different kinds of light, need not be discussed here.

So, then, reproduction requires light, the need for light calls for growth, and growth in turn is possible only through the action of light in photo-synthesis, or the creation of new organic matter by the combination of water and carbon dioxide.

This necessary combination of water from the soil and carbon dioxide from the air can be effected only by exposing the cells containing water to the air, so that the carbon dioxide may be absorbed by these cells. The important feature ecologically is that such exposure inevitably results in considerable losses of water; and even though the cells so exposed may be somewhat protected, it is evident that carbon-dioxide absorption and water loss must, in a given plant, run about parallel, both being controlled by the size of the stomatal openings. The actual water loss, of course, will vary according to the dryness of the air, the concentration and vapor pressure of the contents of the exposed cell, and the intensity of the light in which the operation is performed. Thus a plant capable of making use of diffused light, or largely of the so-called actinic rays, may function with less water loss than one exposed to the full heating effect of sunlight.

Until the distribution of essential substances, such as phosphorus, in the plant has been more fully and carefully studied in relation to light and the volume of the water stream, it is impossible to form a fair opinion as to whether the latter, and the transpiration of a large volume of water, are really essential to the end for which the plant exists. On this point botanists have ever been at variance. For the present, however, transpiration is believed to be merely an unavoidable concomitant of carbon-dioxide absorption, serving no useful purpose when carried to extremes, while always menacing the existence of the plant.

There is now only one more very essential point to be touched upon—a point which is of especial interest in connection with the study of trees because of their perennial character. The continuous absorption of water at the roots and its loss at the leaves of plants is necessarily accompanied by the absorption of all salts which are contained in the soil solution. There is undoubtedly some so-called selective absorption in the sense that any semipermeable membrane admits the complex molecules less readily than the simple ones, but the ability of the plant to differentiate between useful and unnecessary salts is not admitted. It is therefore inevitable that the leaves should accumulate quantities of material which can not be used; that there should be a tendency for such materials to diffuse back toward the roots; that when such material is present in sufficient quantities it should be precipitated or crystallized, and in such form should tend to obstruct the flow of water in the channels where it exists. It is conceivable, then, that all tissues which are actively engaged in the transport of water must eventually become "silted up" with this useless material and that this is the cause of senescence. Its best illustration is, perhaps, in the petiole of the broad leaf, through which narrow passage a large evaporating surface must be supplied. This conception explains quite well the eventual failure of leaves to function and their gradual drying and falling, even in those forms in which the leaves are not in the least sensitive to seasonal changes. It also, perhaps, explains the formation of heartwood in trees. The more important idea, however, is that it points to the necessity for growth to maintain existence. It is not sufficient that the "suppressed" tree (as every forester calls the tree growing with insufficient light) should obtain enough water to prevent the desiccation of the foliage. The plant must be periodically enabled to produce some new growth or it succumbs to senility, regardless of age. Apparently the maturity of a normal or even a dominant tree is attained soon after its limit of height is reached, as it is then limited in its extensions for light and soon can not make the needed annual additions to its transporting system.

It is hoped that this discussion will clarify the point of view which prevails in the discussion of the individual environmental conditions.

MEASUREMENT OF ENVIRONMENTAL CONDITIONS AFFECTING FOREST VEGETATION.

The character of the forest and its very existence are determined by the climate, soil, and subsoil of the locality. The general character of the region, including the character of the vegetation and of the soil, is determined in the highest degree by the climate. The climate affects the region and vegetation in two ways: (1) It is at present the most important factor in the environment of the vegetation; (2) it has affected the present environment in its historical development; for instance, in the formation of the soils, their present physical and chemical composition being largely the result of the past climate in combination with other natural factors. The determination of the important features of a climate is not a simple matter. It must rest upon a sufficiently long series of observations at well-equipped meteorological stations.

CLIMATIC CHARACTERISTICS OF LOCALITY.

NATURAL CLIMATIC REGIONS.

The characteristics of a climate must be studied first of all by natural regions and the study based on the observations of several stations located in different parts of the same region. The climate of individual localities may best be analyzed by comparison with the climate of the entire natural region in which the locality is found or of a control station centrally located.

DATA OBTAINED BY WEATHER BUREAU.

For general climatic studies of the forest regions, and to some extent in studying the conditions for growth in established stands, the data collected by the United States Weather Bureau at its numerous regular stations may be used to good advantage. At the greater number of these stations only data on air temperatures and precipitation are obtained. At the larger stations data on humidity, sunshine, barometric pressure, etc., are obtained, but because of the almost universal location of such stations in towns and cities the applicability of the data to forest conditions is often very questionable. It appears, therefore, that the regular observations of the Weather Bureau will furnish us principally with precipitation and temperature data by which the broader forest regions may be defined. The use of these same data in strictly local studies will depend entirely on the minute examination of the conditions surrounding the station.

KNOWLEDGE OF EXISTING WEATHER BUREAU STATIONS NECESSARY.

Before attempting any meterological observations the investigator should visit the nearest permanent meteorological stations and obtain a clear understanding of the manner in which the observations are made, compare his own instruments with those of the station, and ascertain the natural conditions in which the permanent station is located and the extent to which they are typical of the region. This is essential to enable the investigator to decide whether and to what extent he would be justified in connecting his special meteorological observations with those of the permanent station. Observations at permanent, well-equipped Weather Bureau stations are not always conducted in the way that meets the special needs of the investigator. There may be observations essential to the forester which are not being made at all. Furthermore, the data of the permanent station will not always enable one to judge of the effect of the climatic conditions upon forest vegetation. For instance, the measurements of the temperature of the air are always made at a regular Weather Bureau station at some height above the ground and in a more or less open place outside of the forest; while to the forester, the temperature of that layer of the air in which most of the forest vegetation is found has the greatest significance. Again, while a very precise measure of precipitation may be of no use to the investigator, the amount falling in single storms may vary so greatly in short distances that a record obtained a few miles away will be very misleading. It is thus evident that forest research has special meteorological problems, and that usually the long-established weather station may serve better as a control than as a definite point for obtaining information about forest conditions.

COMPUTATION OF ALL WEATHER DATA BY PERIODS OF GROWTH AND REST.

One essential thing to be kept in mind is that plants may react to the climatic conditions in altogether different ways during periods of growth and rest. To analyze the reactions of plant life it is usually desirable, therefore, to compute climatic data by such periods. They may be based either on a knowledge of the particular plant formation which each observation-point represents, or on the average period of the native vegetation of the locality. Usually it will be preferable to adopt first a "growing season" for the whole region under study. Later, for more exact comparison of the component formations and after careful determination, the specific periods of plant activity may be employed in summarizing temperatures, etc.

SPECIAL OBSERVATIONS ON CLIMATE AND SOIL OF LOCALITY.

To obtain concrete information on restricted localities and specific forest types it will be necessary in most instances for forest investigators to establish apparatus and make observations independently. In the more important respects the accepted procedure of meteorologists and the standard instruments may be used by the forest investigator, but the latter will also require many data not obtained in routine meteorological work, and, especially in the location of instruments, will be compelled to vary procedure according to local needs.

LOCATION OF INSTRUMENTS FOR THE STUDY OF THE GROWTH OF FOREST STANDS.

Atmospheric conditions affecting the growth of forest stands as a whole should naturally be measured at a distance from the ground which will represent the mean height of the sensitive portion of the tree; that is, the mean elevation of the crown. Thus, if a stand were generally devoid of green limbs for the first 10 feet of the stems and had an average total height of 70 feet, the observations should be at $10+\frac{70-10}{2}$, or 40 feet from the ground. Measurements of the light received by the stand should obviously be made at an elevation where none of the light is intercepted. The same result may sometimes be obtained by measurements near the ground in a large opening on the same site. Soil conditions should be measured at all depths which the roots of the trees may be reasonably expected to reach. The depth will be less in heavy than in light soils. In general, however, it is believed that an extreme depth of 4 feet is sufficient, though any evidence to the contrary should change the procedure. The rule of measuring soil temperatures at the surface and at 1 and 4 feet may be followed. If it should appear necessary in using the data, the temperatures at other depths may be obtained by plotting the known values and by interpolating on the curve which may be drawn for any given period, assuming the temperature at 20 or 30 feet to be always equal to the local mean annual temperature. Similarly, soil moisture may be determined at the surface and at 1, 2, 3, and possibly 4 feet and, by projecting the curve formed by plotting the moisture of these points the moisture at greater or intermediate depths may be approximated.

LOCATION OF INSTRUMENTS FOR THE STUDY OF CONDITIONS AFFECTING REPRODUCTION.

It is only logical to assume that, before a definite plant formation or forest type can be developed, there must exist conditions favorable to germination and development of the small and very sensitive seedlings. The forester is often concerned only with the problem of "securing reproduction," realizing that, once the seedlings of a given species are established, the future of the stand is quite definitely assured and practically beyond his ability to influence. In forestry particularly, because perennial plants are the subjects of study, the seedling stage presents the most acute practical problems and those most deserving of scientific study. What bearing this has on the methods to be followed in ecological investigations may be readily illustrated. If, for example, it should be noted that seedlings of a given species die in great numbers during their first or second winter and it is desired to determine why such losses occur and whether they are preventable, it might be deemed necessary to study the rate of evaporation and the amount of drying to which such seedlings are subjected during periods when the soil is frozen. Obviously, it would be necessary to determine this period precisely and to know (1) when the soil was frozen throughout the root zone of the seedlings, and (2) when it was frozen at the surface so that moisture obtained below might not reach the aerial portion. On the other hand, the atmospheric stresses and the tendency toward evaporation losses generally might be measured, that is to say, for the locality and at a convenient spot; but it would be apparent that if the seedlings under observation were covered by snow the rate of evaporation above that snow layer would have no significance whatever.

The point, therefore, needs the greatest possible stress that, in the investigation of many of the particular problems of reproduction and distribution of the species, the investigator must be concerned with the immediate conditions of the surface soil and the atmospheric and solar conditions at an elevation barely above the surface soil, in connection with germination, with survival before the seedling becomes well rooted, and with possible injury through heat or drought at the soil's surface before the young stem is protected by an effective corticle. Measurements at depths of even 1 foot in the soil, or at elevations of a foot above it, will usually only be made to give general, comparative indications of the conditions which it is really necessary to understand; and because the rapidly fluctuating conditions of the soil's surface are in many ways extremely difficult to cope with.

In considering the conditions which affect reproduction, an elevation of 6 inches above the surface may possibly be accepted as the lowest level at which aerial measurements are practicable, but by the exercise of ingenuity it should be possible to improve on this. In soil study, greatest attention must be paid to the near-surface conditions. The actual moisture of the covering of litter and humus, as well as that of the first mineral soil, is obviously important, but extremely difficult to measure with any great accuracy, especially as the humus layer is seldom the same on any two spots which might be selected, and may change in moisture content almost as rapidly as the atmosphere. It is almost inevitable, therefore, that actual moisture measurements should be confined to the first layer of mineral soil and to greater depths if desired, and that the depth and character only of the humus should be noted, using some predetermined rule for estimating its moisture content at various times. For soil temperatures conditions at the surface are doubtless of the greatest importance; but here again the measurement of the actual and constantly changing soil conditions presents a practical difficulty. Measurements below the surface may have considerable comparative value, even though they do not give the extremes which may have the most direct bearing on plant life; and it is therefore suggested that a depth of 1 foot be taken in all such studies as furnishing a kind of control for other observations.

Having considered the general arrangement of apparatus, the matter of exact methods and instruments to be used in measuring each aerial and soil condition may now be taken up.

AIR TEMPERATURES.

Air temperatures are more readily measured than any other condition because of the simple equipment required, and they will probably be most frequently considered at temporary stations. It is hardly to be questioned that air temperatures affect growth very directly, although this may not always be apparent if only periodic and annual mean temperatures are considered. It is also fairly apparent that the air temperature which is adequate for the growth of an individual plant receiving an abundance of light may be quite inadequate for one growing in competition with or in the shade of other plants. Then there are the maximum temperatures to be considered, which it now seems may be more directly operative in preventing the extension of plant ranges than any other temperature condition. In this connection, the temperature of the soil surface may be most important, but that of the air layer just above the soil must not be overlooked.

The following problems summarize briefly what are believed to be the most important temperature problems in relation to forestry.

PROBLEMS.

1. Temperature zones, as indicated by mean monthly, seasonal, and annual air temperatures, or length of frostless season, or temperature sums (hour degrees) above a fixed minimum (say, 40° F.), which furnish the conditions necessary for the existence of a given species.
2. Actual rate of growth in height, diameter, volume, or weight of any species, within different temperature limits, should preferably be

determined under controlled conditions of moisture supply and sunlight.

3. Especially in connection with the preceding, and as integrating air temperature and sunlight influences, leaf temperatures should be measured as a more direct criterion of the temperature conditions regulating food production and growth. What is particularly sought, of course, is the relation between leaf temperatures, air temperatures, and sunlight, and whether or not this is essentially different in different plants. It is probably necessary to determine general relations of this kind and to base observations of growth on long-term air temperature records.

4. The maximum temperatures which may be tolerated without highly destructive reactions in the plant, leading to fatal results, have been investigated very little and apparently have received very little weight in considering problems of distribution, although a number of investigators have shown that growth-rate falls off rapidly beyond a certain optimum temperature. The difficulty of observations on this point lies in the extremely close connection which is likely to exist, under any natural conditions, between very high temperatures and excessive transpiration or positive drought in the soil's surface.

In the general study of climatic or temperature zones affecting plant distribution and life forms, Merriam's (30)[2] work has become classic. The more minute determination of forest zones may begin with comparison of mean temperatures or temperature sums above a minimum of about 40° F., or similar sums for the frostless period. Livingston (25), in a general survey of the temperatures of the United States, carried the matter one step farther by rating the chemical efficiency of temperatures above 40° F., according to the van't Hoff-Arrhenius principle of doubled activity for each 18° F. increase in temperature. These temperature efficiencies were then summed for the growing season, in place of the original temperatures. Sampson (32), McLane (31), and Lehenbauer (24), have tried various modifications of the Merriam idea of temperature sums, all of which should be looked into. One will hardly escape the conviction that the consideration of any temperature term other than the mean temperature will require the accumulation of hourly temperature records or, in other words, the use of the thermograph.

In the more exact study of the rate of growth as influenced by temperature a greater number of technical problems are presented. The temperature coefficient can not be determined unless moisture and sunlight are under control. The actual measurements of growth rate are difficult, and necessitate first of all plants of uniform age and size for the various comparisons. It seems to be quite well established that growth of most plants begins at about 40° F., is very slow up to about 60° F., and reaches a maximum at, perhaps, 80° F. These points will be at least suggestive of the temperature ranges and temperature groups to be considered. It will, however, probably not be satisfactory to merely note that a given growth was secured in A hours in temperatures between T and T_1. MacDougal (27) suggests the summation of temperatures from what may be called the base of each temperature range (say, about 60° F., but not more than 65° F.), and as the simplest means of obtaining hour-degrees in each temperature range has used the planimeter to measure the area on thermograph traces included between any two given lines.

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[2] The figures in parenthesis refer to the bibliography at the end of this bulletin.

The study of leaf temperatures is not a study of the environment, but will be at least a means to a better understanding of the action of the environment and will, perhaps, lead to more comprehensive and expressive measurements of the environment. A good deal of rough work has been done in measuring the temperatures of leaves, usually by wrapping them about the bulb of a thermometer or placing the latter in close contact with them. Such methods, however, are wholly inadequate for treating the needles of conifers, and are of doubtful value elsewhere. E. Shreve (36) has made use of the great sensitivity and possibly small bulk of a thermocouple, to devise an apparatus which will readily reflect the temperature of any part of a leaf with which it is brought into contact. The whole equipment seems sufficiently compact and practical to furnish great usefulness in the field as well as in the laboratory.

With this sketchy consideration of the problems which should be faced, the ordinary means of accumulating temperature records may now be mentioned.

EXPOSURE OF THERMOMETERS.

Comparisons of air temperatures under different conditions can, of course, be made only if the measurements are made in such a manner as to eliminate radiation influences. Radiation measurements or "sun temperatures" undoubtedly have their places, but are not to be confused with the present subject and they will be discussed later.

To measure correctly the temperature of the air, direct or reflected sunlight must be excluded from thermometers as fully as possible. At the same time, the shelter which affords this protection must not itself absorb the radiation sufficiently to become heated within. This danger is largely overcome by allowing free circulation of air through the shelter, and the danger is still further lessened when the air circulation is naturally strong. Such radiation is particularly to be guarded against in any kind of shelter placed on or near the ground. The standard type of shelter is double-roofed and has a partly open floor, and walls made of slats which overlap to exclude light from any overhead source without causing complete stagnation of the air within.

Modifications which would still more fully overcome the heating of the shelter have been proposed by Köppen (23), who would provide artificial air circulation, but such provisions will hardly be necessary for any ordinary thermometric work. On the other hand, the observer can not be too strongly urged to provide shelters which will give the maximum of light protection without preventing the natural air currents from coming in contact with the thermometers. To obtain true nocturnal temperatures near the ground it may be desirable to use a shelter without a floor, so that radiation from below the thermometers is retarded as little as possible. In the work at the Fremont Experiment Station, Bates has found that a shelter for ground temperatures need be no more than a hood, fully open to the north and below the thermometers. If there should be considerable reflection from the north at midday, it could be largely eliminated by an absorbing screen set a foot or two from the hood.

STANDARDIZING THERMOMETERS.

The present possibilities of correlation between temperatures and plant behavior do not justify the greatest precision in thermometry. Units smaller than 1° may be ignored in field work, for all practical purposes, though personal taste may dictate that tenths of degrees be recorded. The essential thing is that only reliable thermometers be used, as the errors in cheap thermometers are not uncommonly as great as the difference between two conditions which are being studied. Even the standard types of maximum, minimum, and mercurial thermometers may well be critically examined and compared with a standard before being used. The Bureau of Standards (37) calibrates such instruments at a nominal cost.

With recording apparatus, such as the air thermograph, adjustment takes the place of standardization. The use of any such recorder, without thermometers to check its accuracy at frequent intervals, can not be recommended.

MAXIMUM, MINIMUM, AND CURRENT TEMPERATURES.

Where only maximum and minimum thermometers are available, of the standard Weather Bureau pattern, the maximum and minimum temperatures for the preceding 24 hours should be recorded once each day, either before 10 a. m. or after 4 p. m., and at the same time the current temperature, as indicated by the minimum thermometer, should be recorded, also the time of the observation. The current temperature is principally of value for making a thermograph correction, and the height of the thermograph pen should therefore be recorded at the same time.

When readings are taken in the morning, if there is no thermograph record by which the time of the maximum and minimum may be determined, the minimum then read should be tabulated on the form for "Air Temperature Record," as of the current day, and the maximum as of the preceding day. If readings are made in the afternoon, both maximum and minimum should be credited to the current day. The current temperature should, of course, be credited to the day on which taken. The instrumental corrections should be used when entering the data in the field, if cards therefor have been prepared, the card being tacked in a conspicuous place in the instrument shelter.

The daily range—purely a computed quantity—in degrees and tenths should be the difference between maximum and minimum temperatures as tabulated for any calendar day.

HOURLY TEMPERATURES.

Where a thermograph is available the instrument should be set in the same shelter as the maximum and minimum thermometers, and hourly temperatures may be obtained therefrom.[3] Corrections for the thermograph trace should always be obtained from the readings of the maximum and minimum thermometer, as thermograph records are liable to considerable errors; but the hours to which these corrections are applied may well be a matter of judgment with the observer, depending on the shape of the temperature curve.[4] The tabulation of hourly temperatures when obtained will require the special form, "Hourly (Air, Soil, or Actinograph) Temperatures." Certain data therefrom will be entered on the "Air Temperature Record." For example, as a measure of conditions affecting growth rate, it may be desirable to know, besides the mean:

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[3] In any ordinary comparison of the temperatures of plant habitats, hourly temperatures are not likely to be used except to explain transient phenomena. However, the thermograph is an extremely valuable adjunct in determining the maximum, minimum, and mean temperatures, not only helping to correct errors of observation but making possible the more exact determination of the extremes and temperature ranges for any period, such as the midnight-to-midnight day, which is the unit of time in most meteorological computations.

[4] Various rules for applying corrections to thermograph traces are used by different students. It is obvious that errors may exist in the traces from two distinct causes: (1) When the range of oscillation of the pen is too great or too small the thermograph may read correctly at medium temperatures but be high and low at the two extremes; (2) even if the pen is approximately correct in its possible range there is a lag due both to the lesser sensitiveness of the thermograph as compared with a mercurial thermometer and to the friction of the pen upon the paper, so that normally the pen does not quite reach to the extremes indicated by the thermometers. In the first case, it is essential that the error be distributed somewhat according to the temperatures; thus, if the pen read correctly at a temperature of 45, at all temperatures above 45—the range of the pen being too great—there would be a minus correction for the trace, and at all temperatures below 45 there would be a plus correction. On the other hand, if the instrument is properly adjusted, it is logical to apply a minus correction to all descending portions of the trace and a plus correction to all ascending portions, the amount of such corrections to be determined from the corrections at the minimum and maximum, respectively.

Form 5.

AIR TEMPERATURE RECORD.

[U. S. Forest Service physical survey]

Type ————————; *Station No.* ——; *cover/open (mark out one); height of thermometers above ground* ——— *feet; for the month of* ————————, *19*—.

Date.	Max.	Min.	Current.		Daily Range	Mean.		Number of hours with—			Snow on ground.	Frost in morning.[1]	Remarks.	Observer
			Time.	Temp.		$\frac{\text{Max.}+\text{Min.}}{2}$	Hourly	32° or below.	33–41°.	42° or above.				
	°F.	°F.		°F.	°F.	°F.	°F.				(Indicate by X.)			
1														
2														
3														
4														
5														
6														
7														
8														
9														
10														
Dec. mean														
11														
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21														
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26														
27														
28														
29														
30														
31														
Dec. mean											No. days	No. days		
Total mo.														
Mean mo.											(a)	(a)		

[1] Killing frosts should be indicated by xx.

Obtain all of the following data from maximum and minimum thermometer records:
Mean temperature for ——— days with snow on ground ——— °F.
Mean temperature for ——— days with no snow on ground ——— °F.
No. freezing days without thawing (max. not over 32.0°) ———. No. freezing days with thawing (mean 32.0° or less, max. over 32.0°) ———.
No. cold days (mean 32.1 to 41.0°) ———. No. cool days (mean 41.1 to 50.0°) ———. No. moderate days (50.1 to 60.0°) ———.
No. warm days (mean 60.1 to 72.0°) ———. No. hot days (mean 72.1° or above).

Prepared by ....

Form 6,
Temp. hourly
Sl
T-1. D-2.

HOURLY (AIR, SOIL OR ACTINOGRAPH) TEMPERATURES.

Type ————————; *Station No.* ——; *cover open (mark out one); distance of instrument above or below ground* ——— *feet; for the month of* ——————, *19*—.

Day.	Hourly temperature [1]—Degrees Fahrenheit.																								Sum.	Mean
	A. m.												P. m.													
	1	2	2	4	5	6	7	8	9	10	11	Noon 12	1	2	3	4	5	6	7	8	9	10	11	Mt. 12		
1.																										
2.																										
3.																										
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28.																										

29																										
30																										
31																										
Sum																										
Mean																										
Corr. for hour																										

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[1] For air, entries in degrees and means in tenths; for soil, entries in tenths and means in hundredths; for actinograph, entries in degrees; no means.

Prepared by ....

The number of hours with temperatures 32° or below.
The number of hours with temperatures 33° to 41°.
The number of hours with temperatures 42° or above.

FROSTS.

Since the actual freezing of foliage may have some very definite effects on plant functions apart from the temperature effect, the occurrence of frost on the ground in the morning should be noted and recorded at the time of regular observations. This notation is especially important in cases where air temperatures near the ground are not being recorded. If the latter are available, records of occurrences of 30° F. or below may be taken in lieu of frost observations. This record should also be tabulated on the "Air Temperature Record." It may be of value in determining at least a normal growing-season for some types of vegetation.

MEAN TEMPERATURES.

It is generally accepted by climatologists that the mean temperature for the day is sufficiently well represented by the sum of the maximum and minimum divided by two. This is probably less satisfactory in the forest, however, than in most open situations where insolation and radiation are not interfered with. Where a thermograph is in use, a nearer approach to the true mean may be obtained from the sum of the hourly temperatures divided by 24. Means for the day should be entered to the nearest tenth degree Fahrenheit. Some of the problems connected with computations of means are described by Hartzell (22).

The means for the decades and the whole month, in all temperature columns, should be obtained and entered to the nearest tenth degree. The following computations are suggested for valuable comparisons of growing conditions. They should be made and entered at the foot of Form 5. All should be taken from the maximum and minimum temperature records, since it is likely that some of the stations to be compared will have no hourly records.

Mean temperature for days with snow on ground.
Mean temperature for days with no snow on ground.
Number freezing days without thawing (maximum below 32°).
Number freezing days with thawing (mean 32° or below, but maximum above 32° F.).
Number cold days (mean 32.1° to 41.0°).
Number cool days (mean 41.1° to 50.0°).
Number moderate days (mean 50.1° to 60°).
Number warm days (mean 60.1° to 72.0°).
Number hot days (mean 72.1° or above).

ANNUAL SUMMARY.

The annual summary of air temperatures on the " Summary " form should be a tabulation by decades and months of the means or totals obtained from the " Air Temperature Record," with the annual mean or total, as the case may be, computed therefrom. Usually a separate " Summary " form will be used for each datum to be summarized.

In addition, as a part of the annual summary, there should be worked out the mean or total for each datum for the growing season. The limits of the latter may be determined, as indicated by the discussion in earlier paragraphs.[5] Whatever the criterion as to the actual length of the growing season, it should be considered to begin and end with even decades, and all means computed for the growing season should be the sum of the decade means divided by the number of decades.

Form 10.

[U. S. Forest Service, Physical Survey.]

SUMMARY.

Type ----------------------; *station No.* ----; *datum* ----------------------;

height or depth ------.

Year.	Decade.	Month.												Mean annual.	Mean growing season.
		Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.		

[Determined by comparing annual means for 1 foot and 4 feet.]

INSTRUMENTS.

	Approximate range of prices.
Thermometers and shelters:	
Mercurial thermometer (Weather Bureau pattern)	$1.25 to $3.00
Maximum thermometer (Weather Bureau pattern)	2.50 to 5.00
Minimum thermometer (Weather Bureau pattern)	1.50 to 3.00
Maximum and minimum thermometers are often supplied in pairs.	
Support for maximum and minimum thermometers	2.00 to 2.50
Instrument shelter, complete, without supports	20.00 to 30.00

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[5] As a matter of fact the temperature conditions that delimit the growth of plants, and especially of coniferous trees are not known, and to attempt to fix a rule for determining when the growing season begins and ends would, at this stage, be extremely arbitrary.

Recording instruments:

Thermograph, complete, with a year's supply of blank forms, pen and ink	$70.00
Combined air and soil (or water) thermograph, complete, with bulb and connecting tube 10 feet long; a year's sup- of blank forms	105.00
Extra length tube (above 10 feet) for above instrument per foot	.50
Thermograph, short range of temperature (probably duty-free prices)	32.00
Thermograph, large range of temperature (probably duty-free prices)	42.00
Recording thermometers, dial type, with one or two pens and bulbs	$75.00 to 150.00

SOIL TEMPERATURES.

Soil temperatures are probably even more important in forest study, especially when questions of initiation and distribution are involved, than air temperatures. Opportunities for obtaining data on the former will probably be more restricted, because of the greater difficulty and expense of installing satisfactory apparatus. They are at present measured at very few, if any, Weather Bureau stations.

It should be strongly emphasized that the study of soil temperatures is in a primitive stage, and that the devising of both instruments and methods offers great opportunity for the investigator, especially in the search for the exact, controlling conditions of the soil's surface. The present discussion does not attempt to consider all the special investigations which are undoubtedly needed, but confines itself largely to routine methods, by which a broader survey of soil temperature conditions may be gained, making possible regional and site comparisons on something like a standard basis.

PURPOSES TO BE SERVED.

The number, and to a considerable extent, the method of soil temperature observations to be made, will depend on the object. Some of the purposes to be served may be summarized as follows:

1. Rather general comparisons of temperature conditions in different plant formations and regions. For this purpose, soil temperatures may have some advantage over air temperatures, in that the former reflect to a considerable degree the amount of insolation received at the ground; and it must be admitted that air temperatures, without radiation measurements, really give no indications of the temperatures experienced by the plant. For this broad purpose, temperatures at a depth of one foot are perhaps most satisfactory.

2. Very careful comparisons of the extreme temperatures to which plants are subjected on the various sites. There is much reason to believe that maximum temperatures are often the forbidding factor in the extension of the range of any given species and that they react

mainly upon the very young seedling at the ground-line, where temperatures are usually highest. The proper investigation of this subject certainly demands surface measurements, but temperatures at a depth of a foot or more may give some indication of the surface condition. The actual measurement of surface conditions presents great technical difficulties, which will be pointed out later.

3. Determination of soil freezing, not as a directly operative temperature condition, but in relation to the availability of soil moisture. In this connection it must be borne in mind, of course, that soil moisture may become essentially nonavailable at a temperature as high as 34°; and, again, that it may not actually freeze until a temperature of 30° or lower is reached. Soil temperatures for this purpose must therefore be coordinated with some data on the soil itself and on the plants involved. It is obvious that, to serve the purpose, frequent observations may be necessary. Continuous thermograph records are preferred because, while most forest trees are not sensitive to freezing for short periods, if at all, in the consideration of moisture even a short period of relief through thawing may mean the beginning of a new cycle of observations on the effect of drought. In the study of soil freezing, the surface or near-surface temperatures are perhaps most important, but it is not entirely certain that mere freezing of the surface soil will stop the movement of water through the main root and stem. It is the part of caution, therefore, to examine the entire root zone, and it may perhaps be necessary to know the conditions of the tree itself as regards freezing at a point near the ground line.

PROBLEMS.

The problems, then, to which soil temperatures are related, are even more numerous than those concerning air temperatures and involve more directly the relations with initiation, habitat extension, and plant succession, rather than rates of growth. Some of the most evident problems may be listed as follows:

1. Optimum temperature of the soil as a seed bed, in direct effect on rate and amount of germination.

2. Optimum temperature of the soil in stimulating osmosis in the roots and hence rate of growth.

3. Minimum temperature at which water is available, or sufficiently available to supply transpiration.

4. Temperature at which the soil freezes and cuts off the plant entirely from water, length of such periods, and atmospheric conditions conducive to transpiration during such periods.

5. Maximum temperatures of the soil or soil-surface which may be tolerated without injury to root or stem of the young, shallow-rooted, and barkless seedling.

6. Influence of air temperatures and light upon soil temperatures, especially maxima, with different kinds of soil cover.

7. Correlation between soil temperature and extremes of drought in the surface soil. It should be noted that the distinction between drought injury and heat injury to young plants is often very difficult, as is shown by Hartley's (44) work. Also, that the soil surface can not for long be excessively hot without becoming arid.

Time of Observations.

The daily range of temperatures at the surface of the soil may be considerably greater than in the air above, and for the study of surface conditions the thermograph is essential. The time of observation of thermometers used to check this instrument should be a time when radiation and absorption of heat in the surface soil are about equal, or, in short, in the early morning. At no other time will a real check be found possible, because the thermometer and thermograph are not equally sensitive to changes and do not absorb direct sunlight equally well.

The daily range of soil temperatures at a depth of 1 foot or more is so slight that it is unimportant, except in its bearing on the question of determining the mean for the day. The latter must often be obtained from a single daily reading of soil thermometers, and must be based on a knowledge of the diurnal oscillation for the particular site. The daily range at 1 foot will seldom, if ever, exceed 5° F., and at 2 feet it is far less; so that, at greater depths than 1 foot, almost any time of the day is suitable for obtaining approximately a mean temperature. The time of observations may therefore be made to accord with other observations without any serious disadvantages.

The point of this discussion is that it is not satisfactory merely to compare the soil temperatures of several sites for a certain time of the day, since at that time one soil may be cooler than the mean temperature for the day and another above the mean.

Daily Mean Soil Temperatures.

The simplest way to secure a proper comparison of sites in respect to mean soil temperatures would, of course, be to determine the maximum and minimum for each day and to average these, as is commonly done with air temperatures. However, as will be pointed out in the discussion of apparatus, registering thermometers for this purpose have not been satisfactorily developed; so that, at present, dependence for a complete record must be placed on one of the several types of soil thermograph, supplemented by frequent readings of a thermometer.

Granting that a full and satisfactory record of soil temperatures may be obtained by the use of the thermograph, it may still, because of the cost of this instrument, be impossible to obtain the desired comparison of a number of sites. The best alternative would seem to be to make one thermograph serve for a number of stations by placing it successively at the several stations until the nature of the diurnal oscillation, for a given season, has been worked out for each station. These oscillations will depend so greatly on the character of the insolation, that a curve for one point could hardly be expected to apply at any other point. With a mean daily curve, however, a single thermometer reading each day may give a very good basis for approximating the mean soil temperature for the day. If this is convenient, the reading may be timed to accord with the most probable hour for the mean temperature to occur.

With hourly soil temperatures for a period of a week at any season, tabulated on the "Hourly (Air, Soil, or Actinograph) Temperatures" form, the mean hourly temperatures may be computed, as well as the mean for all of the days concerned. From the former may be obtained a correction factor for any hour, which, added to the reading for a similar observation hour will give approximately the mean temperature.

For instance, a study of station A-1 at Wagon Wheel Gap, Colo. (steep northerly exposure), at midsummer, showed that the daily oscillation was about 1.35°, that the mean temperature was approached very closely at 7 a. m. or 7 p. m., the minimum not occurring until 2 p. m., and that the correction for a 9 a. m. reading, on 6 days, varied from +0.10° to +0.50°, with a mean correction of 0.34. Similarly at station A-2 (south exposure), it was found, that the aproximate mean would be read at 5 a. m. or 4 p. m., that the minimum occurred at noon, that the daily oscillation was 2.37°, and that a 9 a. m. reading must be corrected by —0.88° to give the mean for the day. Corrections for six individual days varied from —0.50° to —1.35°.

Moore (11) states that at a depth of 3 feet daily oscillations are not felt. It is believed that they are, as a rule, too small even at 2 feet to warrant consideration, although in excessively insolated soils the procedure described for 1-foot temperatures may be followed.

Another method which suggests itself for determining the probable variation from the mean of any daily temperature reading at a fixed hour is to compare the annual mean temperature at the shallow depth with the mean for 4 feet or greater depth where, it may be assumed, the daily values are not affected by regular oscillations. For, while at any time the deeper soil may be cooler or warmer than the surface, the deeper soil always evincing a definite "lag" when changes are in one direction, still there is no basis for assuming that for whole years there can be any essential difference. Therefore, if, for example, the mean annual temperature at 1 foot, as shown by 8 a. m. observations, is 49°, and the corresponding temperature at 4 feet is 50°, there is every reason to believe that the 8 a. m. readings at 1 foot give values, on the average, 1° below the corresponding daily means. When the oscillations are greatest at midsummer, this correction would be too small, and in winter it would be too great; but its use should, at least, bring us nearer to the true mean temperature for any given period.

Table 1 indicates the correction factors thus obtained for a number of stations and sites, with sufficient description of each to show why the morning temperature is much or little below the mean for the day. Practically all of these records were obtained from thermometers in iron pipes, which, by conduction, tend to create a greater daily range of temperatures in their vicinity than occurs in the soil naturally. From these data it will be seen that a small variation from the mean is likely to be secured if (1) the aspect is easterly so that the site receives early insolation, or (2) if the observation hour is relatively late, or (3) if the natural daily range is small, as is usually the case with heavy cover and to some extent on slopes which do not receive vertical rays. Finally, insolation late in the day, though probably causing a large daily range, may bring a morning observation relatively high on the descending curve. These data will be principally valuable in indicating that every site must be studied independently.

TABLE 1.—*Probable error in mean 1-foot soil temperatures obtained through single daily observations.*

[Determined by comparing annual means for 1 foot and 4 feet.]

Site.	Station.	Average depression of 1-foot temperature.	
Moderate southerly slope open	F-1	2.92	8 a. m., strong radiation.
Southwesterly slope, some trees	F-2	1.01	Insolation late in day.
Northeast slope, steep, heavy cover	F-3	0.71	Insolation early, range small.
East slope, some cover	F-4	0.34	Insolation early.
Canyon bottom, heavy cover	F-5	1.40	Insolation late, if any.
Northwest slope	F-6	1.17	Do.
North slope, no cover	F-7-8	1.10	9 a. m., some insolation early.
North slope, full cover	F-9	0.94	9 a. m., little insolation.
Flat, little cover	F-11	1.19	7-8 a. m., heavy snow blanket.
Do	F-12	0.78	8-9 a. m., insolated all day.
North slope, one-third cover	F-14	1.11	9 a. m., little insolation.
Do	F-15	0.97	Do.
North slope, high altitude, no cover	F-16	1.38	10-12 a. m., radiation intense.
Gentle easterly slope, little cover	M-1	0.64	8 a. m., early insolation.
North slope, steep, cover	W-A1	[1] 0.38	9 a. m., small daily range.
South slope, steep, some cover	W-A2	3.16	Great daily range.
North slope, heavy cover	W-F	0.34	11-12 a. m.

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[1] This station equipped with telethermoscope, so that depression is due solely to normal depression of soil temperature at 9 a. m.

READINGS.

All readings of soil thermometers should be in degrees and tenths. Where suspended soil thermometers are used, the readings should be made with the greatest possible speed after removing the thermometer from its seat, and care should be exercised not to expose the thermometer bulb to the sun, even though it be encased. Thermometers on the surface of the soil should be read, if possible, without frequent disturbance of their contact with the soil.

With standardized thermometers the correction may best be applied before recording the reading; but if centigrade readings must be transposed to Fahrenheit, or the reverse, it may be best to make the instrumental correction and the transposition in the office simultaneously.

TABULATION.

The daily observations may be tabulated on the "Soil Temperatures" form. Where two observations are made in one day, both should be entered on the line for the day, with the mean for the day computed from each, and the average of the two computed means in a separate column. Where more than two observations are made, it will be best to enter all at their respective hours on the "Hourly (Air, Soil, or Actinograph) Temperatures" form, and to enter on the "Soil Temperatures" form the mean of all readings without any corrections, provided the three or more readings are distributed well between the times of maximum and minimum temperatures.

HOURLY SOIL TEMPERATURES.

Whenever the soil thermograph is used, or when eye observations are made at frequent intervals, the hourly values should be tabulated on the "Hourly (Air, Soil, or Actinograph) Temperatures" form. With the complete record, the means by hours as well as by days should be computed for any period covered.

In addition, from the hourly record, the maximum, minimum, and mean for each day (midnight to midnight) may be transferred to the "Soil Temperatures" form, in order that the mean may be compared with that obtained from thermometer readings, and that the daily range may be shown.

The application of corrections to the soil thermograph trace can not follow the same rules as are used with air thermographs, because of the difficulty of making corrections of the maxima and minima at the time. If the correction of the soil thermograph trace varies considerably in amount from day to day, the amount of the correction at any hour should be determined by its position with respect to the preceding and following correction hours. If the correction at, say, 9 a. m. is about the same from day to day, one correction may be

Form 4. [U. S. Forest Service, Physical Survey.

SOIL TEMPERATURES.[1]

Type ______; *Station No.* —; *Cover* / *Open* *(mark out one); for the month of* ______ *19*—

Date.	Temperature surf.		Temperature —— feet.					Temperature —— feet.				Automatic record —— feet.						Ob-sever.	Remarks.
	Hour read.	Ob-served temp.	Hour read.	Ob-served temp.	Cor. for time.	Com-puted mean.	Aver-age.[2]	Ob-served temp.	Cor. for time.[3]	Com-puted mean.[3]	Aver-age.[2]	Max.	Time of.	Min.	Time of.	Mean.	Daily range.		
1.																			
2.																			
3.																			
4.																			
5.																			
6.																			
7.																			
8.																			
9.																			
10.																			
Dec. mean.																			
11.																			
12.																			
13.																			
14.																			
15.																			
16.																			
17.																			
18.																			
19.																			
20.																			
Dec. mean.																			
21.																			
22.																			
23.																			
24.																			
25.																			
26.																			
27.																			

28.																			
29.																			
30.																			
31.																			
Dec. mean.																			
Total mon.																			
Mean mon.																			

	Surface.	1 foot.	—— feet.
No. days soil frozen (below 32.0° F.)			
No. days soil cold (32.1° to 41.0°)			
No. days soil cool (41.1° to 50.0°)			
No. days soil warm (50.1° to 60.0°)			
No. days soil hot (60.1° or above)			

[1] All entries in degrees and tenths.

[2] Use "Average" column only where two readings are made in one day. The mean at 1 foot should be the average of the two computed means, which, if both corrections for time were exactly right, would be equal, but which are likely to vary by a few hundredths. When more than two readings a day are made, enter on Form C, and enter here only the average of the three or more readings.

[3] If the 8th to 12th columns on the form are used for readings at 2 feet or more, the two columns marked need not be filled. The column "Average" will be used as indicated above, when two readings are made in one day.

Prepared by ....

applied to all the hours of the day which it represents. This implies, of course, that the range of the instrument has been adjusted before it is placed in service.

SUMMARY OF SOIL TEMPERATURES.

In addition to the means by decades and months, the "Soil Temperatures" form may show the number of days, for each depth at which readings are taken, with temperatures below 32° F. (frozen); with temperatures 32.1 to 41.0° (cold); with temperatures 41.1 to 50.0° (cool); with temperatures 50.1 to 60.0° (warm); and with temperatures above 60° (hot).

ANNUAL SUMMARIES OF SOIL TEMPERATURES.

The "Summary" form may be used for a summary of one or several soil temperature conditions, such as the mean temperatures by decades, months, growing seasons, and years, or the number of days of each temperature class in each month. In the case of surface temperatures, the mean and absolute maxima and the daily ranges are doubtless of great interest. As many forms as necessary may be used.

It may be found that a given soil temperature sufficiently delimits growth so that the occurrence of such a temperature marks the beginning and end of the growing season. This has been the idea in suggesting a division of temperature computations at 41° F. or 5° C., such a temperature being approximately the minimum for activity of lower forms of plant life, as shown by numerous experiments.

APPARATUS.

The most simple apparatus for measuring soil temperatures is the encased soil thermometer, having a stem of sufficient length so that the mercury appears above the surface of the ground when the bulb is at the desired depth. As ordinarily made, however, this thermometer is not only very expensive but is inadequately protected from exposure to the elements and to mechanical forces. For this reason it is not desirable for permanent stations, but will probably in many cases be useful where observations are temporary and light equipment is desired.

For permanent stations the most serviceable apparatus that has been thoroughly tried is an ordinary thermometer suspended by a cord in a 1-inch iron pipe, whose lower end may be sealed either by a cap or by welding. The latter is preferable where the pipe must be sunk to any great depth, since the welded pipe may be formed as a wedge and may be driven into position without seriously disturbing the soil. The pipe should, in all cases, be long enough to extend well above the ground and above any ordinary snow covering, and the upper end should be capped, the suspending cord being attached to the inside of the cap. A welded pipe may be driven in almost any soil if the upper cap is screwed on tightly, and a mallet is used in driving, or wood is placed between the cap and hammer used. An iron hammer directly applied will tear the cap to pieces in a few blows.

The conductivity of an iron pipe is so great that its use for soil temperatures at a depth of 1 foot or less introduces serious complications. Wood or porcelain tubes are therefore necessary.

A porcelain wall tube, such as is commonly used in wiring buildings, may ordinarily be obtained in lengths up to one foot or more at electrical supply shops.

For a relatively permanent installation of thermometers at a depth of about a foot, wood tubes turned and bored in a woodworking shop are very satisfactory. The tube should have some taper, and the lower end should be pointed, so that it may be driven into a smaller hole that has been made with a bar. A wood which does not split readily should be used. When completed, the tube and its plug should be boiled and cooled in a bath of creosote and linseed oil, to prevent swelling, shrinking, and cracking. The top of the tube may be turned with a slope outward, and the plug similarly turned, so that rain water does not enter readily. A tube which has proven very satisfactory in Forest Service work is shown in figure 1.

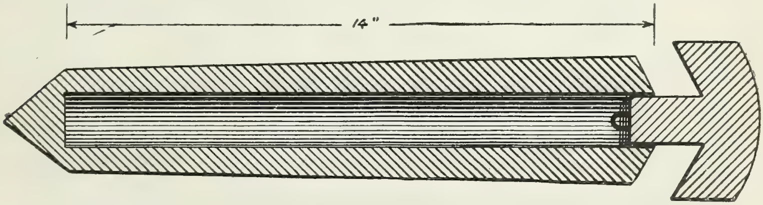

FIG. 1.—Sectional view of turned wood tube for soil thermometers at a depth of 1 foot. Telethermoscope (electric resistance thermometer) with one bulb and recording galvanometer $245; extra bulbs, each $15, connecting wire, per foot about $0.10.

A satisfactory tube for temporary use may be made by cutting a piece of 2 by 2 inch lumber 14 inches long, boring a 1-inch hole through from end to end, capping the lower end with a piece of tin, and cutting a plug to fit in the opening at the top. Two inches of the tube should be left above ground. It is hardly feasible to prepare this apparatus in greater lengths; in fact, for depths of 2 feet or more, the iron pipe is to be preferred.

In order to obtain reliable readings with a thermometer which must be lifted to read, it is necessary that the bulb of the thermometer be in some way protected from immediate contact with the air. This is done either by placing it in a cork, by wrapping it in tissue paper, by sealing to the thermometer an empty cap or vial, or by sealing on a vial filled with alcohol. Covering the bulb, of course, retards the movement of the thermometer which changes of soil temperature, but this is unimportant as compared with the sudden changes which would result from bringing the naked thermometer up into the air. The thermometer to be used in these tubes should be the Weather Bureau "mercurial thermometer," and may be kept attached to the aluminum frame which affords much needed protection.

The use of registering maximum and minimum thermometers in soil temperature work is not very satisfactory. It is true that the standard Weather Bureau types of these instruments may be used on the surface of the soil almost as well as in the air. The following precautions, however, should be observed:

1. To bring the thermometer into close contact with the soil and to avoid unnecessary conduction the metal frame should be discarded.

2. The minimum registering thermometer should be protected from insulation in the middle of the day, since such thermometers ordinarily will not bear temperatures in excess of 120° F. Also, there is some tendency to distill the spirits and break the spirit column at high temperatures.

3. The thermometers must be nearly level.

Maximum and minimum thermometers of the ordinary type are not feasible at any depth, because they can not be kept level.

A maximum thermometer may, however, be used in a vertical position at any depth, provided the stricture of the capillary tube is sufficiently close to carry the weight of the mercury above it. This is technically almost impossible to accomplish, but one in a dozen maximum thermometers may serve the purpose.

To use the registering minimum thermometer at any depth, it is necessary that the stem be bent at a distance from the bulb approximately equal to the contemplated depth, and that the scale fall entirely in that part of the stem above the bend, which is to be horizontal. There is, of course, a limit beyond which this form of construction can not be safely carried, since the alcohol in the stem, as well as in the bulb, reflects temperature. An additional difficulty is in the distillation that has been mentioned, but this may be largely overcome by sufficiently high air pressure above the spirit column.

For permanent stations the use of the telethermoscope or electric-resistance thermometer may, in some cases, be advisable; but this apparatus is expensive and delicate, can not be installed except with considerable disturbance of the soil, and is subject to serious errors if, for example, the batteries become weak or the galvanometer is not perfectly leveled. Especially where great precision is necessary, as in determining the character and influence of surface temperatures, the telethermoscope offers great possibilities.

The soil thermograph is desirable for continuous records of soil temperature which can hardly be obtained with any other instrument, and particularly for measuring the extremes, which it is almost impossible to obtain with registering thermometers. These can be had only after careful adjustment of the range of the pen, or by frequent checking against a thermometer, at high and low temperatures, after the instrument is installed. This instrument should at least be employed wherever new stations are being established, and until the daily curve has been worked out for each season. The securing of a record with this instrument is very similar in its routine features to the work with air thermographs. There is, however, one feature of the soil thermograph which deserves special consideration. This is the tendency, whenever the instrument is moved and the connecting tube suffers more or less deformation, for the whole apparatus to go through a gradual readjustment. One frequently finds the pen steadily ascending or descending for a week after any change. For this reason it does not appear practicable to calibrate or adjust the recording apparatus to agree with an accurate thermometer before placing the instrument and its bulb in their final positions. The Ecological Society, in outlining methods for a systematic soil temperature survey, however, recommended calibrating soil termographs by placing the bulb in a pan of water with the thermometer, and after placing the bulb in its final position in the soil trusting completely to the accuracy of the thermograph.

It is believed, in view of what has been said, to be absolutely necessary to have a thermometer so placed in a wooden or porcelain tube that its bulb is at the same level and practically in contact with the bulb of the themograph, and to obtain frequent comparisons of the thermograph and thermometer.

Special Suggestions on Surface Measurements.

It has been stated that the extremely high temperatures attained at the surface of a well-insolated soil seem to have an important bearing on the initiation of plants, and that technical difficulties make the actual measurement of this surface temperature almost impossible. Doubtless this could be accomplished from time to time with a supersentive plate such as constitutes a part of the leaf-temperature apparatus, but the problem of recording the maximum attained in a day or a season would still be unsolved.

It should be admitted, therefore, that a record of the maximum temperature at the soil's surface can only be approximated with present equipment, for the very simple reason that the object which is to indicate the temperature can not be expected to react to insolation quite as the soil does, nor to be exactly in temperature equilibrium with the soil.

Since the technique has not been well developed, the following suggestions are made in the hope of obtaining somewhat comparable results by different investigators.

1. The bulb of the (maximum-registering) thermometer or the bulb of the thermograph should be exactly half buried, the object lying in a horizontal position. The lower surface may then be a little coler than the surface of the soil, but the exposed surface may be a little warmer.

2. In order that the thermometer or thermograph bulb may have absorptive capacity for insolation similar to that of the soil studied, the exposed surface should be coated with linseed oil, and while this is still moist enough soil should be sprinkled upon it to form a thin coating. It may be necessary to repeat this at rather frequent intervals.

3. The thermometer or thermograph should be disturbed as little as possible, since, if the soil about it is kept loose, it will not be normally moist and will not have the temperature of undisturbed soil. A maximum thermometer of the ordinary type must, of course, be raised for setting, so that for frequent comparisons of thermograph and thermometer, the ordinary cylindrical-bulb mercurial thermometer may be most satisfactory.

4. Provision must be made for recording temperatures far in excess of those of the air or deeper soil. It will be safest to allow for an excess of full 100° F. over the 1-foot soil temperature, wherever direct insolation is received during several hours of the day.

Instruments.

For mercurial thermometers, combined air-and-soil thermographs, and recording thermometers (equally adapted to air, soil, and water measurements), see "Instruments" listed under "Air temperatures":

Special soil thermometers, wood encased, with stem long enough to be read above the surface of the ground, for depths of 6 inches to 3 feet	$6.00 to $10.00
Soil (or water) thermograph, with connecting tube, pens, ink, forms, etc. (bulb is about 1 inch by 12 inches)	85.00
Soil thermograph	------
Telethermoscope (electric resistance thermometer) with one bulb and nonrecording galvanometer	95.00
Switch for 6 thermocouples (Galvanometer requires about 3 dry cells)	16.00

SOLAR RADIATION—LIGHT.

The importance of light, at all stages in the development of trees, has never been underestimated by foresters. On the contrary, reviewing the literature of forestry at the present time, it would seem that this element of the environment has been emphasized, by some almost to the exclusion of all the other conditions. It was, perhaps, only natural that casual observers of the forest should mention this factor more frequently than all others, because the presence or absence of light is so easily detected. It must now be admitted, however, that visible light does not tell the whole story; and, furthermore, that phenomena, commonly called by foresters the "suppression" of trees, which have often been credited to insufficient light, may be and probably are in many instances caused by lack of moisture.

In this country Zon (77) citing experiments of Fricke, was one of the first to call attention to the relatively great importance of factors other than light. It may be that his suggesion created too strong a reaction, that there has been too much of a tendency on the part of American investigators to ignore light or to be satisfied with an incomplete study of its ecological relations. It is believed, however, that this is only apparently the case, the situation being explained by the large amount of ecological study that has been performed in the western mountain forests, where sunlight is not deficient and precipitation or soil moisture appears usually to be the more vitally controlling factor.

On the other hand, the work of Burns (56–59) shows substantial progress in the study of light. Its effects on growth have been directly observed, and its bearing on the transpiration rate and water requirements of young trees is, at least, strongly suggested. Pearson (12), Clements (60), and many others have made observations on light under less controlled conditions. The principal lesson to be learned from the progress to date, however, is that light can not be taken independently without regard for other conditions that it modifies and all of the plant functions which it stimulates. Nowhere, perhaps, is a better illustration found of the danger of one-sided ecological investigations than the common error of foresters in ascribing all bad effects of crowding in the forest to lack of light.

CONCEPT OF THE FUNCTIONS OF RADIANT ENERGY.

The solar radiation available to the plant not only supplements the heat available by conduction from the air but is vitally necessary to the chemical activities of the plant, of which photosynthesis is foremost and of most direct interest to the ecologist. It is fairly evident that sunlight has an influence on the temperature of leaves and other plant parts of which we obtain only a partial measurement through ordinary air temperatures. That this is an important condition affecting distribution of every species is evidenced by the fact that with increase of both altitude and latitude, or, in short, with decrease of air temperature, a given plant seems to require more light for its development. This evidence is not in itself conclusive, because, on a given site, more light obtained by wider spacing will usually mean more moisture, which may often be the controlling factor. Again, in a given locality, the species which thrive best in air of low temperature always seem more tolerant of shade.

Perhaps it is best to analyze the situation at the outset according to physical principles and logic rather than on the basis of questionable evidence. The latter has been mentioned to forewarn the student of some of the pitfalls of poorly conceived observational methods.

The radiant energy available to the plant may consist of an infinite variety of rays or wave lengths, from the most subdued heat to the ultra-violet light. The effect of each of these wave lengths is entirely dependent upon the nature of the absorbants in the plant. Thus the organic material of the cell walls and the water within the cells are capable of absorbing readily the red and infra-red or "heat" rays of the solar spectrum. The chloroplasts show an ability to absorb visible rays, the proportionate absorption of the various wave lengths varying in different plants. Of the absorption of ultra-violet light by leaves practically nothing is known as yet on account of the difficulties of observation in this end of the spectrum. We may, however, safely assume a considerable absorption of these invisible rays.

There is practically no question that each of the chemical elements found in the plastids (or, for that matter, anywhere in the leaf cells) absorbs the kind of rays which it would absorb under any other condition. Thus the "selective absorption" by different plants may be mainly the resultant of different amounts and proportions of such of the elements as iron, sodium, and potassium.

All rays which are absorbed are heating, and all may assist in bringing about chemical reactions, of which the first in importance to the plant is the union of H_2O and CO_2 to form carbohydrates. The function of the chlorophyll and of the chloroplasts is to concentrate sufficient energy at a given point to effect this difficult combination. The kinds of rays which are essential to photosynthesis, therefore, are the kinds which the substances in the chloroplasts are capable of absorbing; and, as has been said, the substances may vary according to the kind of plant and according to the solutes which the soil is capable of supplying.

On the other hand, if the chloroplasts find themselves in a medium of cell sap which is cold, it is perfectly evident that the energy which has been concentrated in them through the absorption of a special assortment of rays may be dissipated to the surrounding medium by the simple process of conduction. The rate of conduction will decrease directly as the temperature of the cell sap approaches that of the plastids. It is thus seen that both radiant energy and heat of the air, which may serve to warm the leaf as a whole, do have an influence on photosynthesis; and that for a given intensity of sunlight there must be a leaf temperature below which photosynthesis can not be effected, because of the dissipation of the energy in the plastids. This leaf temperature will depend on every atmospheric condition, including the air temperature. The most important factor tending to keep the leaf temperature below the air temperature, is the use of any available heat in the water-vaporizing process of transpiration. This consumes a very large proportion of all the heat obtainable from all sources. The loss of water and consumption of energy is, presumably, to be looked upon as an unavoidable consequence of the need for stomata to admit carbon dioxide.

THE NATURE OF SUNLIGHT.

Biologists must enter upon the measurement of radiant energy, or even upon a discussion of the subject, with the greatest hesitancy, realizing (1) that the physicists' conception of energy is, at this writing, undergoing a change almost daily; (2) that investigations of the solar constant and of sky radiation have made enormous strides during the last two or three decades, creating a vast array of equipment none of which are of proven value, and leaving the whole situation in a state of flux; and (3) that these investigations have shown beyond question the constantly changing quality of sunlight, due both to variations in the sun itself and to absorption in the earth's atmosphere. Realizing these things, it must be admitted that the past investigations of light in connection with forestry and other biological subjects are, practically without exception, obsolete and of no assistance in looking into the problems of the future.

It can not be attempted in this discussion to predict the line of endeavor for future investigators in light. Plainly it is a problem for specialists only. A few of the most fundamental facts or principles which, it seems, must govern the method of attack at this time, may, however, be pointed out.

1. As to the character of sunlight, probably the most important point to be borne in mind is that it is an extremely variable quantity, both as regards its whole energy and its constitution of various wave lengths. Setting aside for the present the fact that the emanations from the sun vary periodically in total intensity and also in wave

length, it is necessary to consider the constantly changing absorption by the earth's atmosphere. According to Very (75), who cites Langley (Professional Papers of the Signal Service, No. 15), there are "two different kinds of selective depletion which the solar rays suffer in traversing the earth's atmosphere. One kind is greatest for the rays of shorter wave length, and diminishes by perfectly regular gradations as one passes toward the longer waves of the infra-red. Its cause may be referred to selective reflection or diffraction of the shorter ether-waves by particles of excessive minuteness. The other kind of absorption produces irregular gaps or depressions in the spectral energy curve, which begin at the red end of the visible spectrum and grow in magnitude and frequency as the wave length increases. Researches by Abney and Festing, and by other investigators, have traced the majority of these depressions to the action of aqueous vapor." In the extreme infra-red there is shown to be almost total absorption from this source.

The light, principally of the shorter wave lengths, which is diffused by minute particles in the atmosphere, is not entirely lost, but may be measured as skylight, probably of greater wave length than the original direct rays. The infra-red rays which are so greatly absorbed by the vapor of the atmosphere, merely heat the upper atmosphere, and to this extent, of course, are lost as solar radiation.

2. Looking at the matter from another viewpoint, and accounting for the rather regular daily change in sunlight intensity at a given point on the earth's surface, Kimball (63) after showing the greater intensity of all wave lengths at midday when the light passes through minimum thickness of atmosphere, makes interesting comparisons of the total and luminous radiation under various circumstances. Radiation from an overcast sky is slightly richer, and radiation from a clear sky markedly richer, in luminous rays, than is direct sunlight. Direct sunlight decreases in luminous richness as the sun approaches the horizon.

3. These few facts point to the uselessness of photometric methods, depending on the chemical action of rays of rather limited wave length, to measure the total radiation or any part of the radiation other than the few wave lengths which may be involved in the particular reaction. Thus, for example, even if it were assumed that silver chloride was decomposed in proportion to the intensity of a given section of the spectrum, a certain reaction with silver chloride might be secured with other wave lengths varying through a very wide range.

Again quoting Very (75), it is seen that photochemical processes are very complex and hazardous as a measure of energy:

> While luminous effects may be regarded as dependent on a certain photochemical action upon the retina, not all photochemical processes are equally

definite and measurable. As M. Radau (72) says: "The red rays and the yellow rays in certain cases continue the work commenced by the violet rays, and in others undo what the last have accomplished. Thus, chloride of silver, slightly impressed by the violet rays, is then blackened under the action of all of the visible rays; and guaiacum, turned blue by the violet rays, is bleached by the more luminous rays. It follows that the chemical action of light is, in general, very complex, and that it can be used for measuring the energy of solar rays only with much circumspection."

The inevitable conclusion is that direct photochemical methods can not be made to solve the problems of ecology, but this does not eliminate spectrophotochemical measurements, which may, in fact, give the best possible criteria as to the variations in the different spectral regions and the effect of such variations on plants.

4. The fourth point to be considered in approaching the study of possible methods for radiation measurements, is the difficulty of securing complete absorption of sunlight. While lampblack is popularly conceived to absorb rays of all wave lengths and to transform them into measurable heat, recent investigations have proved that this is only approximately true, and have shown the existence of an infra-red spectrum of extreme wave length to which lampblack is partially transparent. Fortunately, this region is relatively unimportant as a source of energy and may be, for biological purposes, almost wholly unimportant.

A greater source of error than that arising from the failure of lampblack to absorb the radiation is undoubtedly the loss, as heat radiation, and by conduction and convection, before the heat can be properly measured. It must, of course, be borne in mind that temperature is not a measure of heat, and that the indications of a thermometer can not be used except as the radiation rate of the thermometer itself has been thoroughly studied.

With this conception of the nature of sunlight and the difficulties in the way of its proper measurement, it is perfectly evident that the primitive methods that have been employed in measuring light in the forest do not give satisfactory results. Two distinct but supplemental lines of attack suggest themselves as being profitable:

1. The growing of trees under controlled conditions of light, using both artificial lights of known composition and monochromatic and other screens which will transmit to the plants only certain wave lengths, as suggested in the work which has been started by MacDougal (68): The physiological action of each wave length must, of course, be studied. Through such study it is hoped that the requirements for light may be determined, any actual deficiency in sunlight which exists in the forest recognized, and the effective supply measured.

2. In studying either the light conditions as they exist in the forest or the effective supply suggested by the preceding line of

investigation it is obviously necessary to use spectroscopic methods. Since the growth of a tree requires many years, and even complete suppression in the densest forest is seldom accomplished in less than two or three years, it is evident that in the forest minute examination of every variation in sunlight is unnecessary. An examination covering the entire period of the activity which is being studied must, however, be obtained. The nearly ideal and still practicable arrangement would seem to be provision for continuous observation of the total energy available as radiation throughout the period of plant activity, with sufficiently frequent spectroscopic observation of the composition of this energy to establish not only an average quality analysis for the whole period but also to show the variations which occur from season to season and year to year and their relations to the functioning of the plant.

Unfortunately, spectrum analysis by present common methods does not permit an examination of either the ultra-violet or infra-red spectra. For this reason it has been suggested that all spectrum analyses might be better conducted by means of energy measurements (e. g. thermal effect) than by optical comparisons. This is an almost unexplored field and presents infinite possibilities for the investigator who will devise a satisfactory method of measuring the energy of all parts of the spectrum under both laboratory and field conditions.

HORIZONTAL AND VERTICAL EXPOSURES.

It is perhaps well to point out at this stage that, particularly in forest studies, light measurements of whatever kind may be on two distinct bases. In forestry the growth of an individual tree is rarely spoken of, or even if it is, no practical significance is attached to it, because the individual can rarely be separated from the influence of other individuals. Forest growth, in any practical sense, must be growth (volume increment) per unit of land area. Similarly, if an attempt is made to find a relationship between growth and available light, it is certain that the energy must be expressed in terms of a unit of area inclined at the same slope as the ground. The total energy available to the crowns of trees on a northerly exposure of given gradient, for example, can not be more than that which would be incident upon a plane of exactly the same aspect and gradient. Land areas, however, are always measured in terms of their horizontal projections. It therefore follows that the measurements must be reduced to horizontal areas, and the simplest means for reduction is to expose a given area horizontally for the original determinations.

Determinations of total energy available for growth, however, will rarely be made in ecological studies, which are much more likely to be concerned with questions affecting the survival of the individual plant or tree. The individual tree of any age must be thought of as a spherical, conical, or cylindrical mass of irregular surface, such that a pencil of rays will affect equal absorbing surfaces, almost regardless of its angle of approach. It is therefore logical that, in the study of individual trees, all determinations of light intensity and quality should take as the unit a pencil of rays of given cross section. This full cross section is to be obtained by exposing the absorbing surface of given area normal to the axis of the pencil.

In the following discussion exposures for this purpose and of this nature will be implied, unless light quantities affecting stand growth are specifically mentioned.

Total Radiation on the Site.

To determine the quantity of radiant energy which is available for plants or trees on any particular site in relation to the growth of the whole stand, obviously the quantity should be measured at a point where it has not been intercepted or diminished in intensity. As previously pointed out, this will be above the crowns or in an opening of exposure similar to the plane of the forest canopy. After having determined the total amount of energy available, the amount actually utilized, if desired, might be measured as the difference between the total and that which is available below the canopy. In any event, the intensity of solar radiation may be expressed in heat units, or calories per square centimeter of horizontal area.

Insolation Under Canopies.

The measurement of insolation or sunlight intensity under canopies may be for two distinct purposes: To determine the amount of energy which has escaped the tree crowns above and therefrom to deduce the amount utilized by them; and to determine the amount which is available for undergrowth, either in the form of subordinate species or reproduction. The first measurement, which is not concerned with the tolerance of the species, but rather with the completeness of the canopy, the completeness of utilization, and the rate of growth of the stand should obviously be closely connected with measurements of total radiation on the site. Since the plan of such measurements has been explained, this subject may be dismissed and the attention turned to those problems which are concerned wholly with the question of tolerance, or the question of the relative requirements of the various species for light, especially in connection with survival in their earliest stages.

LIGHT MEASUREMENTS IN RELATION TO MINIMUM REQUIREMENTS.

The tolerance of trees to shade may be determined in any one of four ways:

1. By preparing empirical scales of tolerance, based on experience and long-continued observation of the relative shade-enduring qualities of various species when growing together. This method is obviously very crude, and may be very misleading, since such a condition as soil moisture may determine, as directly as does light, the relative positions of the species in any particular stand. The persistence of individual branches, or rate of pruning; the maximum density of stands composed mainly of any particular species; the ability of reproduction to thrive in shade; all these things may be considered in preparing empirical scales.

2. A second method of determining the tolerance of trees is by study of the structure of the leaves. Having determined the normal relations of the tissues of protective and assimilative characters, leaves may be subjected to different degrees of shading. Those which adapt themselves most completely to a variety of light conditions are naturally those which will survive best if placed under trying conditions as regards lack of light. This method, however scientifically it is executed, can not give us absolute comparisons, since the structures of leaves are so variable even under the same conditions that the exact degree of change of structure can not be determined. In other words, this may give indications, but not comparable statistical data.

3. A third method of determining tolerance is the experimental method, which must, of course, be executed in the laboratory where all other conditions, as well as the supply of light, may be controlled. The primary object is the determination of the minimum amounts of light which will sustain life of the several species under consideration, when all other conditions (especially heat and soil moisture) are nearly optimum. It will be fairly apparent, however, that high temperatures may reduce the light requirement, and low soil moisture may increase it; and, since variations in all of the other conditions will be encountered in the field, it is very desirable that any experimental test should be so conducted that the influence of these other conditions on tolerance may be at least accurately gauged, if not directly measured.

It is believed that the best results will be secured if each species to be tested is grown under a variety of light conditions, approaching both the optimum and the minimum, and if the tests are so conducted that the physiological effects of each light intensity may be expressed finally in terms of growth, or weight accretion, rather than if dependence is placed solely or largely on observations of fatal effects when the minimum light has been exceeded. For example, if seedlings of a given species are grown with 20, 40, 60, 80, and 100 per cent of the full available light, other conditions being equal, and if the greatest accretion is put on by those having 60 and 80 per cent, while those having only 20 per cent barely exist, and some of their number succumb, it will be fairly evident that the optimum is between 60 and 80 per cent, and the minimum slightly below 20 per cent for the given conditions of heat and moisture. Both points may be found quite closely enough by curving the growth data. Similarly, in other temperature and moisture series different optima and minima of light may be found, and the absolute optimum combination may be very nearly arrived at.

On account of the difficulty of duplicating any set of conditions at different periods, it is extremely desirable that the more important species whose relative tolerance it is desired to know should all be treated during the same period, and also that an arrangement should be effected which will make possible different combinations of light with moisture and temperature.

The following plan for such experimental determination of tolerance, while merely suggestive, may assist in initiating some work along this very important line. The arrangements suggested should accommodate about four species. It would, perhaps, be well to run an initial test with rather gross differences in the light quantities, as suggested above, and to repeat at a later date when the knowledge obtained will permit more minute examination of the critical points:

Construct a solarium about 5½ by 8 feet, with its long axis lying east and west, its floor and glass roof having possibly a gentle slope to the south. The depth from glass to floor need not exceed 18 inches. Divide this into three equal parts by means of glass partitions running north and south. If two layers of glass are used throughout, having dead air between them, the purposes will be more completely fulfilled without affecting light quantities appreciably more than would the single layer of glass. Let the higher north wall serve as entrance to the compartments, being closed by a door whose inner surface has very poor reflecting powers.

For each of these compartments 10 pans, each a foot square and 6 inches or a foot deep, will be required. These may be made of galvanized iron with drainage openings in the bottom. Into each pan put a measured quantity of soil, sufficient to fill it to within 2 inches of the top. The pan and dry soil weight both having been determined, the amount of water necessary to maintain a given moisture percentage in the soil may easily be computed, and this, added to the gross dry weight, will give the weight which the pan should show after each watering.

Each pan may now be sown with sufficient seeds of the several species involved to produce a good stand on the area of 1 square foot. Possibly 100 seeds of each species should be used in each, the seedlings later being thinned to uniform density. Unless it is desired to determine the effect of light on germination, this process should be concluded for all pans, under uniform conditions, before they are placed in the solarium. The main operations may be started just as soon as the seedlings are established. Otherwise great care must be used to develop the seedlings similarly in all pans.

Having reached the proper stage, place 10 pans in each of the three compartments; say, in two north-and-south rows. The three compartments are to be maintained at different temperatures; say, at mean temperatures of 50°, 60°, and 70° F., with more or less diurnal oscillation in each. In each compartment one row of pans is to be given sufficient water to maintain its soil moisture at, say, twice the wilting coefficient, while the other row will be maintained at four times the wilting coefficient. The condition of the pans may at any time be determined by weighing and the water supply regulated accordingly. In any row of five pans five different light intensities may be maintained. One pan in each row should doubtless be allowed full sunlight, another should be cut 20 per cent, a third 40 per cent, etc. The amounts may be governed by previously gained empirical knowledge of the requirements, so that the full range of light values will not have to be covered in any case. The shading of each pan separately may be arranged by using covers of punched screen, in which the areas of the openings correspond to the proportion or full light which it is desired to admit. It should be borne in mind at the outset that the glass of the solarium considerably reduces the light intensity, particularly in the infra-red rays. The quality of this light should be compared with that of direct sunlight and means should also be devised for measuring the light intensity under each screen.

The proper heating of the various compartments will prove the most serious obstacle in most cases. This, of course, will have to be accomplished by artificial means and should be done by introducing warm air into the compartments from an outside source in such a manner as to maintain the desired air temperatures without directly heating the pans. The air thermometer and thermostat should be suspended at a mean elevation and protected from insolation.

The positions of pans in each compartment should be frequently changed so that none will profit more than others by localized heat and light optima which are certain to exist.

The final effect of light and also the effect of other factors with light is to be determined by the accretion of dry matter in the seedlings of each pan and species. In order that this may be expressed in net quantities for the time of treatment, some of the sedlings weeded out at the beginning of the test should be dried and weighed.

It is evident that this general plan might be followed in tests to show the effect of different kinds of light on growth, using monochromatic screens as covers for the pans instead of the punched metallic screens, or supplying different compartments of a dark chamber with various kinds of artificial light.

4. The fourth method of determining tolerance or light requirements is similar to that just described, but depends on the measurement of light intensities as they are encountered in the field, and the

correlation of such measurements with observations on the condition, rate of growth, etc., of the trees existing under the measured conditions. The great advantages of this method are that a great variety of light conditions may be obtained and maintained with little expense or trouble and that growth and health of the subjects may be studied through long periods and under natural conditions. One disadvantage is that a variety of light conditions is necessarily accompanied by a variety in the measure of other conditions the effect of which may be confused with the effects of light, and neither of the two sets of effects can be exactly measured and balanced against each other, nor, most of all, can they be controlled. A further disadvantage consists in variation of the amount of shading at any given point with different hours of the day and seasons of the year, necessitating long-continued observations to obtain any expressive results. These disadvantages, however, will loom up less formidably when we understand better what part of the radiant energy is really effective. As has been pointed out, the field method must go hand in hand with laboratory studies.

APPARATUS AND METHODS FOR RADIANT ENERGY MEASUREMENTS.

Although most of the methods of light measurement used by forest investigators have been described as now obsolete, it is impossible, of course, to throw away all that has been gained through experience with different types of instruments. Quite apart from forest investigations, there is available a vast amount of research in the study of light per se which, however incomplete and changing this study may be, represents the starting point for any new work undertaken. It is therefore considered expedient to bring together a list of the methods and instruments which have been used, not in any degree of historical completeness, but rather to show the several lines of study and their possibilities as briefly as possible.

1. In the *radiometer*, which is commonly seen in jewelers' windows, the energy of light is transformed into work. This instrument has no practical value, however, because the work is performed inefficiently and probably does not vary in proportion to the energy received.

2. The *thermopyle* represents the first attempt to transform radiant energy into electrical current. This is accomplished by allowing the light to fall upon the junction of two wires of different metals. The opposing ends of the two wires are also joined, forming a complete circuit. The amount of current generated and passing around this circuit is measured at any point in the circuit by means of a galvanometer. The radiomicrometer, for measuring the heat from stars, is an extremely delicate adaptation of the principle of the thermopyle.

3. The *bolometer* developed by Langley (67), who was a pioneer in investigations of the sun's energy, employs a blackened platinum strip for the absorption of the rays, the thermal effect on this strip being measured by its change in electrical resistance.

4. The later developments along this line, described as *pyrheliometers* are known, respectively, as the Ångström (69), Callendar (64), Marvin (65), and Smithsonian Institution Standard (50). The first three are constructed on the principle of electric resistance thermometers, while the Smithsonian utilizes a mecurial thermometer. The Callendar, it is understood, is distinguished by its automatic arrangements for constantly recording the difference in resistance between the absorbing and nonabsorbing plates or "grids."

The technical differences between the several types of instruments are so involved that a discussion of them can not be undertaken here. They have to do largely with questions of efficiency in absorption and measurement of the energy. In fact, the student of ecology who plans to use any such instruments as these will be compelled to make a most thorough study of the subject. Recent years have seen so much attention given to it by physicists and meterologists that, it may be said, the measurement of solar radiation is in a state of flux. Bigelow (53) has recently questioned the adequacy of any measurements made with pyrheliometers, declaring them useless, at least for the determination of the solar constant. It will therefore be the part of wisdom for biologists to stand aside until the physicists have reached a more stable basis.

In all of these instruments the auxiliary apparatus required is considerable, except possibly with the Smithsonian. This is naturally a deterrent to their use in the field, although the difficulties may always be overcome when we are convinced of the usefulness of the results. An instrument utilizing a mercurial thermometer recommends itself for simplicity; yet, in view of the frequent changes in the light intensity at any single point in the forest, the equipment for continuous recording is not more than is needed for satisfactory results.

5. The *thermometric sunshine recorder* (70), with electrical registering apparatus, is the equipment used at many Weather Bureau stations for registering the duration of sunlight. This instrument is extremely simple in design and operation, involving only the movement of a column of mercury through a tube connecting a blackened and a transparent bulb of an air thermometer. When the mercury reaches a certain height, as the result of air pressure in the black bulb, it completes a circuit with the two platinum wires embedded in the walls of the tube, and the current passing over this circuit operates the registering mechanism.

The apparatus is adjusted by increasing or decreasing the amount of mercury in the tube and by bringing the tube closer to or farther from a vertical position, so that the mercury first reaches the platinum wires when the disk of the sun is visible through the clouds. Any addition to the light intensity above this approximate standard does not, therefore, alter the nature of the record. While the method is thus seen to be extremely crude, the record showing only the presence or absence of light of a rather low intensity, still it can hardly be questioned that such a record of sunlight duration is of very great value in comparing the solar climate of different regions, and possibly also in obtaining a measure of the direct light under canopies; that is, of the approximate degree of shading. There appears to be an untried value in such records through arbitrary rating of the recorded "sunshine" according to the elevation of the sun, and with allowance also for atmospheric humidity.

One objectionable feature of the instrument is the amount of time required to warm it in the morning to the point where it first records. In fact, it is by no means free from effect of the air temperature and must be adjusted to the seasons.

In the lack of a better measure of sunlight values, it seems well worth while to have this sunshine record in forest studies. The form for "Daily and Hourly Sunshine Duration" has been provided for the tabulations of a month.

6. The *solar thermograph* or mechanical differential telethermograph devised by Briggs (54) in the biophysical laboratory of the Bureau of Plant Industry, is in principle the same as some of the soil thermographs; but it is a duplex instrument, in which the temperature of one of the bulbs tends to compensate that of a second. One of the bulbs may be blackened and spherical, with a short tube, so that the bulb is rather easily held just above the case of the instrument, while the second bulb may be kept in the shade.

This arrangement permits the recording of the excess of temperature attained by the bulb in sunlight, limited by the natural radiation and by conduction, which will increase as the air movement increases. The reduction of air movement to practically zero, or the elimination of conduction almost entirely by the use of an evacuated glass case, would make possible the calibration of such an instrument so that the temperature difference between the bulb and the surrounding air might be directly converted into rate of heat absorption by the bulb.

As a matter of fact, an ordinary air and soil thermograph has been used by Bates (105) with a fair degree of satisfaction, to show the variations in sun heat from day to day, the disadvantage of the regular equipment being in the variable surface exposed to the sun at different hours by a cylindrical bulb.

Form 7.
Sunshine, monthly.

DAILY AND HOURLY SUNSHINE DURATION.[1]

Type, ————————; *station No. 2; elevation of horizon from instrument, E.* —°, *W.* —°; *for the month of* ————————, *19*——.

Date.	(For hour ending) a. m.									(For hour ending) p. m.								Total for day.	Total possible[2] for day.	Per cent of possible.	Remarks.
	4	5	6	7	8	9	10	11	12 noon.	1	2	3	4	5	6	7	8				
	Sunshine duration—minutes or tenth hours.																				
1																					
2																					
3																					
4																					
5																					
6																					
7																					
8																					
9																					
10																					
										Decade mean											
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Decade mean

21																				
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24																				
25																				
26																				
27																				
28																				
29																				
30																				
31																				
Decade mean																				
Monthly total																				
Monthly mean																				

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[1] With or without twilight corrections.

[2] Must be determined by observing actual times of sunrise and sunset at the instrument, through all seasons, computing therefrom the possible minutes of sunshine for each day. Morning and evening hours should be given full possible value when it is observed that the twilight periods were perfectly clear; otherwise may best be left blank. No twilight corrections to be made unless regular observation is possible.

Prepared by ——————————.

There is hardly any question that an instrument of this kind may be made to serve the present practical requirements of forest studies, for a measure of radiation intensity. It would be very desirable to have the necessary protection from air currents supplied, without intercepting some of the rays by a layer of glass.

7. *Photo-chemical photometers.*—The objections which have been raised to the use of chemical reactions as a measure of the sunlight intensity can not be overcome. In addition to the fact that the other rays may not vary from time to time in the same proportion as the chemically active rays measured, it is somewhat questionable whether the result secured, as in the coloration of a photographic paper, is proportionate to the product of the light intensity and the time.

In forest studies the photochemical method seems to serve one purpose fairly well, that being to obtain a measure of the density of the canopy. It is then assumed that the amount of light reaching the ground is to the total sunlight as the area of openings in the crowns is to the whole area; or, in other words, that the light coming through these openings is unaltered in its passage. While technically there is also light below the crowns, which has been transmitted through the leaves, and the photographic paper may be sensitive to the rays in this class, it probably does not introduce any serious error, considering the purposes for which such measurements should be used.

This crown-density determination should always be made by moving the photometer through as great a space as possible during the few seconds of exposure.

The Bunsen-Roscoe (55) unit of actinic light is the light required to produce on a standard paper a shade equivalent to that produced by the mixture of 1 part lampblack and 1,000 parts pure white zinc oxide. The details of the preparation of this "normal shade" and the "normal paper" are given by Zon and Graves (78) or may be obtained from the original citation given above. The object in mentioning it here is simply to show that it is possible to carry on photometric observations on a fixed standard.

Likewise, photographic-supply manufacturers have prepared a standard shade, and a standard paper for estimating light intensities. One of the best known of the "exposure meters" is extremely simple in operation. In one opening of a small disk containing the standard paper is exposed the standard color, a permanent shade. In a corresponding opening may be seen a fresh area of the paper. It is only necessary to expose this to the light until it attains the standard shade, noting the time required, to have a very close basis for computing the light intensity. It seems that this simple contrivance may serve the purpose of ecologists quite as well as more elaborate apparatus of the same type.

Weisner (76) used an instrument almost as simple as this, his standard shade and fresh paper being set in a groove in a block of wood, and appearing in openings of a layer of opaque paper.

Clements (6) devised a photometer in which a narrow strip of "solio" or other sensitive paper may be held, having sufficient area for 25 exposures. This strip is placed on the periphery of one metallic ring, which fits snugly inside another. In the outer ring there is an opening one-fourth of an inch square, covered by a slide which is drawn back to make the exposure. In using this instrument the colors obtained on exposure are not directly compared with a standard color. Rather, it is customary to make a scale of shades with each set of observations, consisting of, say, 10 exposures in full light, of 1, 2, 3, etc., seconds. In the later exposures, then, it is only necessary to keep within the limits of the "scale," and the time may be varied to secure the desired shade. If, for example, a 24-second exposure gives a shade corresponding to 7 seconds on the scale for full light, the relative value of the suppressed light is 7/24 or 29 per cent.

The photochemical-photometer method is not satisfactory for any expression of the light in absolute terms, or for comparing quantities in one day or season with another day or season, or for comparing different localities. Of course, all exposures might be compared to some standard shade, but the operation is needlessly circuitous and is made the more difficult by the perishable nature of the record, the need for examining it in dim lamplight, etc. It is therefore believed that, while this method has some value, a similar effort expended in determining absolute light quantities will be much more profitable.

In addition to the above there are instruments of the same principle by which more or less continuous records may be secured. In one such instrument, used by the Weather Bureau a number of years ago, the light entering through a very small opening made its impression as a band across the sheet of photographic paper on which it fell at successive moments. (See Clements (*6*), p. 51.)

8. It is probable that several hundred kinds of *comparison photometers* have been devised, all depending on an ocular comparison of the sunlight to be studied, with a light of known luminous powers. It is evident that such instruments deal only with the luminous rays, and while they rely upon the accuracy of the eye, the method certainly has advantages over the photochemical method in dealing with that part of the spectrum which is least affected by changes in atmospheric absorption. It is not to be supposed, however, that the luminous rays control plant activities.

One of the simplest types of comparison photometers is the smoked-glass type used by Wagner and credited to him by Zon and Graves (78), although undoubtedly invented much before his time.

The smoked glass is in the form of a wedge which is inserted between the eye and the source of light, until the thickness attained by moving it one way or the other is just sufficient to cause complete absorption of the rays. The wedge is calibrated along its entire length, and the comparison is made between the modified light under study and the full, direct sunlight. Since the luminosity of the latter is variable, the results are not, of course, in absolute terms, even if the subjective error were eliminated.

The Sharpe-Millar (73) photometer is a more recent development and probably superior to other photometers using comparison lamps, in that the light is supplied by electric current, and the comparison lamp may be standardized as often as necessary by varying the amperage. Kimball (63), however, in using it through a great range of daylight values, found it necessary to have screens to cut down the intensity of the daylight to the range of the artificial light; also blue-grass screens to reduce the lamplight to the color of daylight (skylight) alone. It is thus seen that a comparison of sunlight with artificial light has various complicating factors, even with the best of photometers.

With certain correction factors arising from the use of these screens the distance of the comparison lamp from the photometric device is made to express directly the power of the illuminating source in foot-candles.

9. *Spectroscopic measurements.*[6]—In the spectroscope the rays of any light are separated according to wave length. This naturally makes it possible to note the presence or absence of those wave lengths which are known to be essential to the plants under consideration, so that spectroscopic observations promise much to the student of ecology. Unfortunately, however, with the ordinary spectroscope, observations must be ocular and confined to the visible or middle portion of the spectrum. Both the highly active chemical region of the ultra-violet and the strong heating rays of the infra-red, are outside of observation.

Zederbauer (79) made spectroscopic observations of the light in the forest, from which he concluded that there is a marked difference between the absorption by pine and spruce, or intolerant and tolerant species, respectively. The former absorb more strongly near the red end of the visible spectrum; the latter more strongly in the violet region. While Zederbauer's observations and his attempt to reproduce the transmitted wave lengths separately by means of monochromatic glass plates, did not lead to any precise results, they are certainly suggestive of the need for spectroscopic measurements, if we are to determine with any degree of accuracy the kind of light available in the forest.

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[6] The present discussion is necessarily very sketchy, because it is largely suggestive of possibilities rather than actual accomplishments in ecological work. For a complete discussion of spectroscopy and its possibilities we must refer the reader to such a monograph as Baly's "Spectroscopy" (52).

It is self-evident that the simplest means for examining into the absorption of various wave lengths by leaves is to examine the spectra of beams of light which have passed through individual broad leaves or layers of needle leaves, charting the marked bands of absorption, and comparing such charts with similar ones for uninterrupted sunlight. Likewise the spectrum of the diffuse light in the forest may be examined, while the spots of direct light which have reached the ground through large or small openings may be expected to show essentially the same character as light in the open.

Such observations, while doubtless of great value in gaining an insight into the difference between species, and representing the first work which one would naturally undertake in spectroscopy, have only limited value because of the difficulty in reducing the absorption evidence to quantitative terms. There would naturally be also a large subjective error.

10. *Spectro photographs.*—Photographs of the various spectra which may be examined in forest studies obviously have an advantage over mere observations in their permanency, and over drawings in their completeness. According to Baly (52), ordinary photographic dry plates are fairly sensitive to rays within the lengths 2,200 to 5,000 Ångström units, or from about the limit of the blue well into the ultra-violet. In the "orthochromatic" plates and films of commerce the tendency toward very rapid action in the ultra-violet region is suppressed by the use of dyes, so that the shades and tones of the visible spectrum are more clearly brought out.

Plates approaching monochromatic value have been prepared for several regions, the principle being in all cases to stain the plate with a dye which absorbs strongly the rays it is desired to bring out. Thus a red-colored dye may be used to bring out yellow and green. According to Baly (52) again, Abney succeeded in preparing a photographic emulsion which was sensitive in the infra-red to 20,000 Angström units, and the solar spectrum was actually photographed to 10,000 Ångström units. Such plates, of course, are short-lived, being very sensitive to heat.

In addition, there are, more recently, so-called panchromatic plates, which have a very wide range of sensitiveness.

Until more is known as to the part which the infra-red rays play in the chemical activities of the plant, it would seem to be the part of wisdom, in spectrographic observations, to use several plates, covering the entire range of the spectrum with as great thoroughness as possible.

11. Finally, in following out this line of thought, the *spectrobolometer* represents the present limit of thoroughness. By measuring the heat energy of every part of the spectrum, all of the results may be expressed in the same absolute terms, whereas the results obtained by photochemical reactions must be in different terms for each of the several reactions which are required to cover the spectrum. Furthermore, bolometric observations permit the comparison of deficiencies in any region with deficiencies in the whole energy of the light as determined by the same means. As has been pointed out, the heat energy in the region of greatest chemical activity is small; but it is not too small for precise measurement, and when once measured it may be transposed to terms of definite chemical reactions, the transposition factor varying, of course, with each wave-length and with each reaction considered.

The Langley bolometer has been briefly mentioned, because it was designed for measurements of the whole energy of sunlight. The following description from Baly (52) indicates the manner in which the same principle was adapted to the most minute quantities.

> In his final work upon the solar spectrum, Langley made use of a new apparatus[7]; the light from a 20-inch siderostat passed through the slit of a horizontal collimator, which possessed a lens of rock salt 17 centimeters clear aperture, and 10 meters focal length. This lens focused the ray upon a prism or grating; the prism was of rock salt, and was 18.5 centimeters high and 12 centimeters deep in the face, and had a refracting angle of 60°. The angular width of the bolometer thread was decreased to 2 inches of arc by using a telescope lens of 5 meters focus; the sensitiveness was thereby increased, and by improvements in the galvanometer the apparatus was made capable of detecting a temperature change of 0.000001° C. The whole spectrometer was of the fixed-arm type, and the spectrum was made to pass over the bolometer strip by rotating the prism. An automatic self-registering method was adopted of recording the galvanometer readings. The spot of light reflected from the galvanometer mirror was focused upon a broad strip of photographically sensitive paper. This paper strip was caused to move slowly in a vertical direction, and in this way a faithful record of the excursions of the light spot was obtained. At the same time the prism was slowly rotated, and therefore this record clearly showed all the temperature changes of the bolometer as the spectrum passed over it. Further, the motions of the sensitized paper and the prism were exactly coordinated, so that the angular position of the prism corresponding to any portion of the galvanometer record could at once be obtained. In this way, since the dispersion of the prism was already known, the wave length of any spectrum line shown upon the record could be found, and also, from the length of the throw of the light spot, its intensity estimated. The delicacy of this apparatus was sufficient to show the D lines widely separated, with the nickel line in between. * * *
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> By means of this apparatus, Langley mapped the solar spectrum as far as 55,000 Ångström units, and observed 700 lines between A and this limit.

12. *Evaporimeters* may be used for a very rough measure of the heating value of sunlight. At first thought it would seem that the rate of evaporation would be an almost ideal measure, since the

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[7] Brit. Ass. Rep., 1894, p. 465; and Nature, 51, 12 (1894).

evaporation of a gram of water requires a nearly constant amount of heat, varying according to well-known laws. The use of evaporimeters, however, has many complicating factors, principal among which is the air itself as a source of heat. If the atmosphere is lacking in moisture and the wind movement rapid, even an evaporimeter in the sun may be cooler than the air and consequently derive heat from the air. On the other hand, when the rate of evaporation is slow, the evaporimeter may be superheated, and some of the radiant energy absorbed will be dissipated into the air by radiation.

The situation is by no means simplified by the use of a pair of evaporimeters, one of which is designed to absorb little of the radiation and the other much or all of it. In this combination, one instrument may be giving heat to the air, and the other has heat conducted to it.

It therefore appears that evaporimeters may only give the broadest possible comparison of light intensities, as, for example, when a number of similarly constructed instruments are exposed to similar atmospheric conditions. The latter, of course, are very likely to be modified by the same factors that modify the light. For these reasons, the method can not be recommended as an aid in the study of present problems.

INSTRUMENTS AND APPROXIMATE COSTS.[8]

Angström pyrheliometers	----
Callendar pyrheliometers	$500.00
Marvin phyrheliometer—not on market. (U. S. Weather Bureau)	----
Smithsonian phyrheliometer (mercurial thermometer). (Smithsonian Institution)	100.00
Sharpe-Millar photometer	100.00
Clements photometer	7.00
Exposure-meters. (Photographic supply houses.)	1 to 5.00
Spectroscopes	20 to 100.00
Thermometric sunshine recorders:	
Sunshine recorder, electric, glass (not filled), G. S. S. No. 12252	3.55
Electrical sunshine recorded, complete	37.00
Extra glass parts, mounted in brass socket, ready for attaching to support	23.00
Registering instruments for use with thermometric recorders:	
Two-magnet registers—	
No. 1. For sunshine and rainfall (using Form No. 1015–B)	140.00
No. 2. For wind velocity and sunshine (using Form No. 1015–C)	125.00
No. 4. For wind velocity, rainfall, and sunshine (using Form No. 1015–E)	140.00
Quadruple register complete (for wind direction, wind velocity, rainfall, and sunshine), with a year's supply of blank Forms 1017, pens, and ink	350.00

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[8] These should not be taken as quotations.

PRECIPITATION.

Precipitation should be measured at as many special stations as possible, but only at those which are fairly permanent. In general, the regular Weather Bureau data collected at a large number of stations will suffice for the purposes of forest investigators. Because of the difficulty of obtaining an average exposure under canopies, precipitation should always be measured in more or less open situations, or above the crowns, except of course when it is desired to determine the amount intercepted by crowns (89).

Since precipitation has no important action on plants until it is added to the moisture of the soil, there can be no object, in a biological study, and especially in a study of forests, in analyzing precipitation data very closely. For this reason there is no need of hourly precipitation records except possibly in a few localities to study the general character of the storms, which, of course, will vary only slightly with the forest types. For this purpose the tipping-bucket rain gauge (93) should be used. Standard eight-inch rain gauges (93), if properly exposed, will serve in most cases, though more valuable results will be secured where it is possible to install shielded gauges. On the whole, however, the gain in catch through the use of the Marvin shielded gauge[9] is hardly of enough significance to justify the additional expense of the installation, at least for any practical benefit to ecology. The methods of measuring precipitation are too well known to need description.

Under certain circumstances, as in situations which can not be conveniently visited every day, it is possible to increase considerably the value of the record by keeping some kerosene in the rain gauge, which will cover the water and in large measure prevent its loss by evaporation. In this event it will be desirable either to pour off the kerosene before attempting to measure the water or to pour both into a glass graduate in which the amount of water can be seen in a few moments, after which as much of the kerosene as possible may be replaced in the gauge. This method needs little modification for the winter period, if the snow is melted before measuring, as ordinarily it would be. It is, however, very desirable to have the snow, as it melts naturally, drop into a seamless basin containing some kerosene. This may be accomplished by placing a loose funnel near the bottom of the gauge.

EXPOSURE OF GAUGES.

While the measurement of precipitation in gauges is very simple, the securing of a true "catch" is much more difficult, and for this reason the greatest care should be used to install gauges in such positions that a near approach to a true catch will be secured. Wind (81) is the factor which usually prevents all of the precipitation of a given area from entering the gauge and which sometimes removes snow from the gauge after being caught. To obtain protection from wind without obstructing the fall of precipitation from any angle, should be the chief aim in the installation of gauges. The ordinary rule is that the edges of the shielding objects should be at an elevation of 30° or less from the edges of the gauge. This rule may be varied somewhat. Where precipitation is usually accompanied by high winds, the angle should be even less than 30°, and the shield, to compensate, must be the tighter. Where precipitation is not so likely to be driven by wind, the angle may safely be greater. A solid shield is less valuable than a partial one, because it may set up eddies in the air currents which will be fully as unfavorable as the direct wind. On the whole, shields consisting of trees or brush are best.

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[9] Designed by the present Chief of the United States Weather Bureau.

SNOW DEPTHS.

The depth of snow and its water equivalent will serve a useful purpose in giving data on the period of dormancy for each forest type, and in indicating the amount of precipitation available at the beginning of the growing season, which in some localities may be the larger part of the precipitation for the whole year (82, 88). The period of dormancy might be obtained more exactly by temperature measurements, but the latter are not possible at present at least on so large a scale. No data that can now be obtained will cover the forest types of the mountain regions so completely as the snow depth records, and the conclusions which may be drawn from them, as to the water supply, will be extremely broad and comprehensive.

SNOW SCALE READINGS.

The work of obtaining snow depth and density measurements by the national forest ranger force, and in cooperation with the Weather Bureau, is already well organized in some localities, and this work is of a nature which may be done creditably by the general forest forces. The same organization may possibly be effected with profit in other localities. While the work was originally designed to furnish data on the water available for stream flow and with that object in view has been discontinued at the end of April each year, there is no reason why it should not be slightly extended so as to serve the purposes of any forest investigations.

The general plan of the work is:

1. To have a large number of snow scales distributed over all the main watersheds and throughout the entire range of elevations and

the entire range of types, read at the end of each month by the rangers on whose districts they are located. The major portion of these scales are in timbered areas because of the necessity of some protection to secure a representative snow cover (90). Many of them, however, are not actually in the forest but in small parks or openings, and some are in patches of aspen or coniferous reproduction. The cover conditions are classified as (a) normal forest cover of mature or nearly mature trees, (b) partial cover, as given by aspen, reproduction, or scattered trees which shade the snow to some extent, and (c) no cover, as in parks or openings. For each snow scale a complete description of the cover and surroundings is obtained. The essential features of this description are listed on the record card for each scale, and the cards are filed serially according to scale numbers, each card carrying the depth and density record for 12 years.

2. The reports from rangers are submitted at the end of each month on postal cards, of which the following is a sample:

SNOW SCALE NO. —.

Snow Report ——— National Forest, for the end of ————— 19—, county ———, main drainage ———, local stream ———.

Depth at scale, ——— inches. Average in vicinity, ——— inches.

Is depth more (+) or less (—) than normal for this time of year? ———

Density measurement: Depth of snow in tube, ——— (inches and tenths); water equivalent of tube contents, ——— (inches and hundredths, as shown by spring balance).

*Density estimate, ——— per cent. (Light, fresh snow should be estimated at 6 to 8 per cent; settled, dry snow at 8 to 15 per cent; drifted, compact snow at 15 to 20 per cent; frozen or wet snow, with ice at bottom, at 20 to 40 per cent.)

The above observations were made by ————— ("myself" or name of other party) on ————— 19—.

(Signature) ____________________,
Forest Ranger.

*Not to be filled by officers having density apparatus.

3. Snow depths are read at each scale by simply sighting over the general surface of the snow and noting the intersection of this plane with the graduations on the scale.

4. For most localities, the density of the snow is estimated from the descriptive data given on the card. Each ranger is expected to make occasional rough tests to determine density, so that he will become proficient in estimating under varying conditions. A few rangers are now furnished with density-measuring apparatus (91) and the number of such apparatus is to be increased as conditions and funds warrant. The apparatus consists simply of a tube in which a core of snow may be taken (its length being noted on the scale outside the tube), and a balance graduated for inches of water. The weight in inches divided by the depth in inches gives the density.

Where density is estimated, the depth and density are entered when the report is received, and the water equivalent may be computed at any time. Where density apparatus is used, it is necessary to compute the density and apply this figure to the depth reading at the scale, which may be somewhat different from the depth noted on the tube.

It is self-evident that, while the progress of snow accumulation throughout the winter is interesting, the most important data are those which show the maximum accumulation just prior to the beginning of rapid spring melting.

TABULATION.

The form for "Daily and Hourly Precipitation" may serve as a monthly summary both for daily observations and for notations from hourly records where these are obtained. The following should be tabulated from daily observation:

Total precipitation in inches of rain or melted snow.

Unmelted snow, as measured in the gauge, in snow bins (*84*), or on the ground. Precise measurements of the snowfall appear to be useless to the ecologist.

Depth of snow on the ground at time of observation.

Number of storms of rain, sleet, or snow which, by the weight of accumulated water or because of accompanying wind, do mechanical damage to trees.

The following data are merely intended to depict the character of storms, and should be obtained from the hourly automatic records for a few stations typical of the different regions and altitudes:

Number of hours having measurable precipitation.
Number of hours having 0.05 to 0.10 inches precipitation.
Number of hours having 0.10 to 0.20 inches precipitation.
Number of hours having 0.20 to 0.50 inches precipitation.
Number of hours having more than 0.50 inches precipitation.

The "Summary" form will serve as an annual summary for precipitation data of both classes and will include all of the data given as the monthly sums or means on the several "Daily and Hourly Precipitation" forms. As usual, sums and means should be computed for the growing season as well as for the whole year.

INSTRUMENTS AND APPROXIMATE PRICES.

Rain and snow gauges:

Rain and snow gauge, 8-inch Weather Bureau pattern	$5.00
Supports, box, for rain and snow gauge	1.50
Measuring sticks, rain gauge, cedar, No. 12236	.15
Rain gauge, tipping-bucket, with supports and measuring tube	75.00

Form 9.

[Precipitation monthly.]

DAILY AND HOURLY PRECIPITATION.

Type ————————; *station No.* ——; *cover open (mark out one); for month of* ————————, *19—.*

Date.	Daily observations.[1]			From hourly automatic records.					No. wind, rain,[4] sleet or snow storms doing mechanical damage to trees.
				Total hours with—					
	Total precipitation (inches).	Snow unmelted [2] (inches).	Snow [3] on ground at obs. (inches).	Precipitation.	0.05–0.10″ per hr.	0.10–0.20″ per hr.	0.20–0.50″ per hr.	More than 0.50″ per hr.	
1									
2									
3									
4									
5									
6									
7									
8									
9									
10									
Dec. total or mean			M						
11									
12									
13									
14									
15									
16									
17									
18									
19									
20									
Dec. total or mean			M						
21									
22									
23									
24									
25									
26									

27									
28									
29									
30									
31									
Dec. total or mean			M						
Month			M						

[1] Enter on midnight to midnight basis where automatic records permit the division.

[2] Gauge catch, unless mats or other reliable apparatus are used on the ground.

[3] In decade and month lines give the mean, not total.

[4] Since probably more than 1 storm a day will seldom occur, the extent of damage may be indicated in this space by the terms slight, moderate or severe, and the nature of the storm by the words, rain, wind, sleet, or snow.

*Prepared by*____________________

SOIL MOISTURE AND SOIL QUALITIES.

The subject of soil moisture is closely related to that of precipitation. Since the physical and chemical properties of the soil are closely linked up with moisture, it seems logical to consider all of these subjects together as a question of water supply, after which atmospheric conditions which particularly affect water losses may be taken up.

There is practically no question that water is the prime requisite of all life, for without water the colloids could not exist. It is hardly more true of plants than of animals that, besides possessing water at any given time, they must be almost continually given new supplies to make up for unavoidable losses; but, with the exception of aquatic species, plants are more at the mercy of the moisture of the habitat than are animals, because they can not move to new supplies—the water must somehow be brought within their reach.

Ecologically, it is perhaps unsafe to say that moisture has more to do with the establishment, development, and succession of a plant society than any other condition, that is, that it controls the character of the plant society more directly. It is perhaps nearer the truth to say that when the temperature conditions are about optimum for a given plant or society, moisture determines success or failure almost absolutely. Yet this does not express the situation, for in a vast majority of cases the plant society must depend at all stages, but particularly at its initiation, upon a proper balance between temperature and moisture, especially as these are integrated in the condition of the surface soil.

In the last analysis all other environmental conditions react more or less on the soil moisture, and the best measure of their influence in this respect is found in a measure of changes in the soil moisture. It is readily seen, therefore, that the direct measurement of the soil moisture is of the utmost importance.

The moisture content of the soil, whether expressed in grams per kilogram of soil or cubic centimeters per cubic meter of soil, does not give directly a measure of the rate at which it may be obtained by the plant, because of the great variation in the moisture-withholding powers of soils. This rate is obviously very important whenever the atmospheric conditions are such as to cause heavy loss from the leaves, and may often determine success or failure of the individual plant and of the society.

OSMOSIS AS A FACTOR IN WATER ABSORPTION.

The rate of absorption is unquestionably dependent upon the simple physical process known as diffusion, which is commonly called osmosis when speaking of plants, since the mixing of the two liquids is somewhat modified by a semipermeable membrane between them which, in fact, tends to make the diffusion one sided. Expressed briefly and without attempting to define the kinetic forces, if there is water on one side of the semipermeable membrane and on the other side a solute in water, there is a constant tendency of the molecules of water to move both ways through the membrane, while the molecules of the solute, being heavier and larger, do not so readily diffuse to the side, where they are deficient in numbers. On the other hand the presence of the solute on one side of the membrane evidently has the effect of suppressing the energy of the water molecules there, so that fewer molecules pass in the outward direction than are coming in through the membrane. This results in an accumulation on one side of the membrane, and, so far as the increasing volume here is restrained, gives rise to a pressure which is termed "osmotic pressure." Actually, the pressure must be due to the energy of the free molecules which bombard the membrane from the outside.

In the case of the plant, there are, in addition to the mineral salts and organic compounds which may be in solution within the root-cells, and within each succeeding cell in greater concentration from root to leaf tip, two additional factors or forces, which undoubtedly have much to do with osmosis. While the forces may be called capillarity and adsorption, respectively, there is no reason for supposing that the action of these forces, so far as water molecules are concerned, is different from that of molecules of solids in solution. In other words, a molecule of a solid, whether acting individually as part of a relatively solid mass or surface or as part of a gelatinous mass like the cell protoplasm, by its gravitational attraction for a water molecule tends to suppress the activity of that molecule and thereby, under the proper conditions, gives rise to the process we call osmosis.

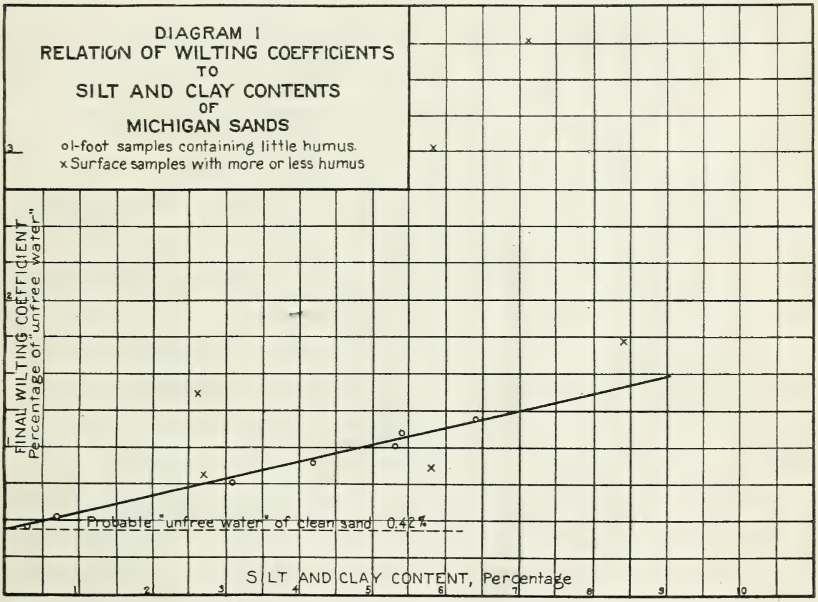
The so-called capillary attraction of the cell walls, which cause them to imbibe enough water to fill their intercellular spaces, can not be considered an important factor in osmosis, for ordinarily this attraction would pull the water as strongly from one side of the wall as the other. In the case of dead wood cells, it may be imagined that a small amount of water is transferred from one point to another through no other action than this capillary affinity of the cell walls.

The really important element in osmosis is, without question, the affinity of the protoplasm for water. While it appears to be true that a cell similar to a plant cell might have the same water content, arising from osmotic pressure and due entirely to inorganic solutes, still the important thing is, not merely that the protoplasm must have a certain minimum amount of water to maintain its properties as a colloid, but that through selective absorption it is able to regulate, at least to some extent, the nature of the solution which shall occupy the space within the cell. The protoplasm, while directly effective in causing osmosis, is undoubtedly regulatory of all the conditions within the cell. It is, indeed, through the study of soils that the present conception of the nature of osmosis and of the importance of the colloids of the plant in this process is arrived at. The work of Bouyoucos (109) followed by Hoagland (127) has been especially instructive on this point. Bouyoucos and McCool (106) first attempted to determine directly the concentration of soluble salts in the soil by measuring the freezing-point depressions of soils in their natural conditions of moisture and with definite amounts of water added to them. At the outset, no doubt, he supposed that, allowing for increased solubility of the soil substances with increased moisture, the freezing-point depressions would increase proportionately as the concentration of the solutes increased by reduction of the whole moisture of the soil. This he found not to be the case, for, while the effect of increasing concentration was shown in greater freezing-point depressions as the moisture was reduced, a point was rather suddenly reached at which no freezing at all occurred. From this Bouyoucos concluded that there must be at all times in the soil a certain amount of "unfree" water, probably not in a liquid state but so adsorbed or chemically combined that at no time does it constitute a part of the soil solution. This water was conceived to be that which is held within the colloidal or clay masses of the soil, but it is fairly evident that, since pure sand may contain a small amount of such water, it may be in part water in extremely thin films, or more probably in the form or independent molecules, on the surfaces of the crystalline particles.

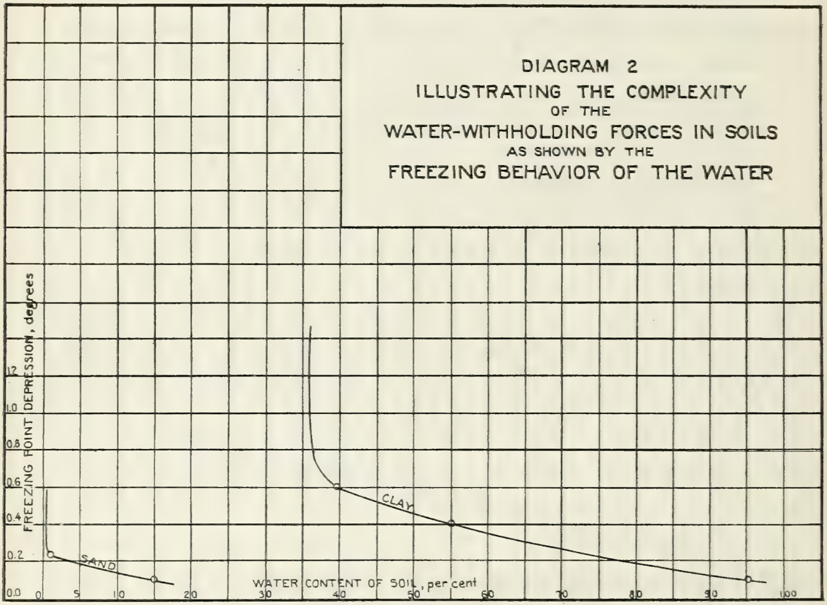
In his later work Bouyoucos (109) succeeded in measuring the volume of this unfree or combined water indirectly, by noting the volume expansion of the whole mass at the instant when freezing occurred. By this means he was able to determine just what proportion of the whole amount of water entered into the freezing process. Adding in every case 5 cubic centimeters of water to 25 grams of air-dried soil, he found that the proportion of this 5 cubic centimeters which did not freeze was only 2 per cent (0.10 cubic centimeters) in the case of a quartz sand, but 60 per cent (3 cubic centimeters) in the case of a clay, and 74 per cent for heavy silt loam.

The exact amount of unfree water for a given soil was found to be dependent on several experimental conditions, which led to the belief that under certain conditions it could be transformed into free water. In other words, there is no fixed point at which the water begins to be unfree, but under given conditions each soil exhibits certain definite characteristics. Thus there was in all soils, except the quartz sand, less water which failed to freeze when 10 cubic centimeters had been added to a standard sample than when only 5 cubic centimeters were used. There was also less when the supercooling was carried below the standard temperature of —4° C., and when the process was repeated on the same sample several times. Without going further into these details, which are readily available in the original article, one more fact should be mentioned, namely, that the moisture contents at which various soils fail to show definite freezing points, and similarly the contents which by the method just described are found definitely not to freeze, bear a close relation to the wilting coefficients of the same soils.

Directly bearing on the point as to the part played by the colloidal masses of the soil, Bates (105) found, for eight samples of Michigan and Nebraska sand, each taken at a depth of 1 foot, and consequently showing a maximum of 2 per cent humus, that there was a linear relation between the final wilting coefficients for jack and Norway pines on the one hand, and the combined silt and clay contents of the respective soils on the other. The latter varied from 0.3 to 6.4 per cent. The behavior of surface soils with larger humus contents was different; but these, when decidedly lacking in humus, might give even lower values than the deep soils, probably on account of more thorough leaching. The results, as shown in diagram 1, indicate that if silt and clay were entirely eliminated, the sands might still possess a wilting coefficient of about 0.43 per cent. This is extremely close to the value for unfree water which Bouyoucos found to be almost constant in the case of quartz sand, regardless of the experimental conditions.



The conclusion is therefore reached that, in the final struggle which determines whether the plant shall obtain sufficient water for its barest existence, there is a contest for water between two colloidal masses, either of which may be able to adsorb the solutes which have been in the water about them, and hence eliminate osmotic action in the ordinary sense of an interchange between two liquids. Apparently this contest between the attraction of the soil particles and clay masses on the one hand, and the cell walls and protoplasmic masses on the other, is not essentially different in principle from osmosis, except that in the final stage of the struggle the movement of a molecule of water from one side of the line to the other becomes impossible because of the lack of a liquid conductor. It is probably on this account that, in a strong clay soil, the plant may wilt considerably before an equilibrium of tensions has actually been produced.



The important point, however, is that under normal growing conditions in the plant and soil there is a set of forces at work regulating the supply of water to the plant, which is dependent almost wholly on the presence of solutes in free water, or osmosis in the ordinary sense; while, when the water becomes relatively scarce (this may be at 20 or 30 per cent moisture content in a clay soil), an almost entirely different set of forces is brought into play. It therefore appears that the study of soil moisture is not so elemental as it has been supposed, and that the value of soil moisture to the plant can not be expressed by a direct linear function of the amount of water in the soil. Diagram 2 is inserted to show the nature of the problem. Forest investigators must get away from this elemental idea, taking up the study of soil moisture at the point to which expert soil physicists have already brought it.

PROBLEMS AND SOME DEFINITIONS.

Such being the general situation, it is evident that the ecologist has a number of related problems to solve before the measurement of moisture has much meaning. In the following paragraphs certain terms have been introduced which will have a rather definite usage in the later discussion.

1. The *total moisture* must be obtained as the basis for all expressions of current conditions in the soil, unless they are measured directly in terms which will give osmotic pressure.

2. The *nonavailable moisture* must be measured with reference to the plant or plants concerned, either directly by wilting tests, or through some established relationship between the *wilting coefficient* on the one hand, and the *antiosmotic pressure* (P′) the *capillary moisture*, the *moisture equivalent*, or the *hygroscopic coefficient*, on the other.

3. The *available moisture* may be expressed as the difference between the total and the nonavailable moisture. Such an expression may have some direct ecological significance in indicating the probable duration of the moisture supply and the life tenure of the plants.

4. The *availability* of the moisture is seen in the general relationship between the available moisture and the total moisture, and may be expressed by a ratio such as 3 : 4, or by a decimal such as 0.75, on an unattainable scale of unity.

5. The *coefficient of availability* is a more exact expression of the relation between the osmotic pressure of the plant (P) and the antiosmotic pressure of the soil water (P′), and is a measure of the possible rate of intake. Thus, if the soil has a freezing-point depression of 0.5°, and the plant of 1.5°, the respective osmotic pressures are $P'=6.025$ and $P=18.04$ atmospheres, and the possible rate of intake is indicated by the difference, which is approximately 12.02 atmospheres. It is perfectly evident, however, that the osmotic pressure in the root tips may be very little greater than the osmotic pressure of the soil, while there may be a very great increase in passing from the roots to the leaf tips where water is being lost most rapidly. As this is also the most convenient point for measuring the osmotic pressure in the plant, and such can here be accomplished without seriously disturbing the plant, it is suggested that the osmotic pressure at the leaf tips should be the basis for expressing the plant condition. In this event, the actual availability of the water is obviously affected by distance, or the mean osmotic gradient from the soil to the leaf tips. The *coefficient of availability* (AA) must therefore be expressed by $\frac{P-P'}{L}$, in which L is the distance in centimeters from the root tip, or point of measuring the soil condition, to the leaf tip.

In addition, for the greater refinement of this expression, it will be necessary to make a correction for the height to which the water must be lifted. In small plants this would be of no consequence, but with tall trees it is evidently the factor which brings the coefficient of availability to zero long before the soil moisture is exhausted. This correction may be taken as approximately 0.097 atmospheres per meter of height. Expressing this whole correction by G,

$$AA=\frac{P-(P'+G)}{L}$$

It should be noted that the availability of the moisture is an expression whose value will change only very gradually with the exhaustion of the soil moisture, and is really based upon an assumed equilibrium between the osmotic pressure of the whole plant and that of the soil at the time of wilting, which it is possible to attain approximately if the wilting of the plant is brought about very slowly.

On the other hand, the coefficient of availability must be constantly fluctuating, being dependent both on supply and demand (loss). Thus the rapid loss of a considerable amount of water from the leaves must be almost immediately reflected in the osmotic pressure there, the gradient from leaves to roots, and the rate of intake at the roots and of transfer from cell to cell. The objects in the use of such an expression must be to show not only how the demands of the plant vary from time to time, but how nearly the demands created by certain atmospheric conditions may be satisfied. Thus some insight is obtained into the conditions governing growth-rate.

6. There are various other conditions of the soil which have an effect upon plants and may or may not be fully indicated by the osmotic pressure of the soil solution at any time. Of these may be mentioned:

(*a*) The hydrogen-ion concentration as an expression of the degree of alkalinity or acidity.

(*b*) The make-up of the soil, and particularly its clay content as indicated by the mechanical analyses.

(*c*) Humus content.

(*d*) The capillary transporting power of the soil, by which water from distant regions may be brought to the roots. Obviously this may often be an extremely important factor in the economy of the plant. Its importance is somewhat minimized when moisture determinations are certainly made in the soil area which is reached by the roots.

(*e*) Chemical content of all elements and compounds, with particular reference to those which are necessary in nutrition.

Total-Moisture Determinations.

The determination of the current-moisture content of the soil at a given point is an exceedingly simple matter, and a vast amount of such work has been done in connection with agricultural investigations and greenhouse experiments; in fact, so much has been done that citations are useless.

On the other hand, repeated determinations at a given point to show changes, minima, etc., immediately introduce complications. When a sample has been taken from the ground, it is very difficult to fill the space with the same kind of soil as before, and even if this were accomplished the new soil would not soon be in a normal moisture condition. The next sample must, therefore, almost certainly be taken a short distance away, and almost invariably this introduces a change in composition, such that equal moisture contents in two successive samples may not have the same plant value. Usually in agricultural soils or well-mixed potting soils, these variations may be ignored. Very often in forest soils, however, the changes in composition are very abrupt; in fact there is often no such thing as uniformity of soil texture, even in a practical sense. The sampling of forest soils, moreover, is often difficult owing to the presence of rocks which make it impossible to obtain a sample at the desired spot, at least with borers of any description. These mechanical difficulties may usually be overcome by the use of pick and shovel, and in careful surveys of the root zones of individual trees or groups such methods will undoubtedly have to be resorted to.

In practice, it is usually impossible to examine a large number of soil points with sufficient frequency to show even approximately the changes in soil moisture. It is necessary to select, more or less arbitrarily, points which seem to represent the average of conditions in the plant formation or forest type under study, and to confine the effort to showing as accurately as possible all the conditions which occur at this point.

SOIL-WELLS FOR REPRESENTATIVE POINTS.

In view of what has been said, it appears necessary to make provision for establishing some standard conditions under which soil samples shall be taken at permanent stations. The ideal method would undoubtedly be to show the moisture content of a single sample of soil from time to time, and it has been suggested that this might be accomplished by the periodic weighing of a standard soil sample contained in a porous cup which would be permanently located at the soil point. This plan involves a number of technical difficulties, and is, moreover, wholly untried. The nearest practical approach to the method of a single sample would seem to be in the plan of soil wells, which has been thoroughly tried at the Fremont Experiment Station and elsewhere.

At each station where soil moisture is to be determined periodically, a well 18 to 24 inches in diameter and 4 or more feet deep may be dug. At the nearest available point a soil quarry is established for each station or group of stations having similar soils. From this quarry is taken soil containing only a moderate amount of humus, and which should be sifted through 4-mesh screen. At the outset sufficient sifted soil is obtained to fill the well and to furnish 1 or 2 cubic feet of reserve, the whole being thoroughly mixed. The sifted soil should be firmly tamped into the well. It will be better if the well may be allowed to stand a year before being used, the soil becoming settled by water action and being to some extent penetrated by roots.

In order to maintain uniform conditions at the surface, each soil well should be kept free of litter by means of a frame of 1 by 4 inch boards, 18 or 24 inches square, which may be slightly sunk in the soil. Over this is placed a slightly larger frame covered with hardware cloth. It is evident that this frame will interfere with surface erosion. The surface of the soil in the well should at all times be kept flush with the surface of the ground around, so that the amount of water available for absorption is not appreciably greater or smaller than elsewhere.

At the time of digging any soil well, samples of the native soil at 1, 2, and 3 feet from the surface and other depths at which moisture is to be determined, as well as one of the prepared soil for the well, should be obtained for testing. Each sample should comprise about 30 pounds and should be air-dried, unless it is to be used immediately.

Each soil quarry should be permanently designated at the time of its first use, and a record may be made of the quality and location of material taken therefrom, so that in the future fresh supplies for the well may be obtained, with a little trial, very nearly like the original.

As such soil wells are used year after year, it will be noted that the finer material is to some extent concentrated in the lower layers, especially if the soil of the well is decidedly sandy and loose. This will not be found so important a change if the soil is compact, or contains considerable humus.

The question naturally arises, how will the moisture in one of these wells compare with the moisture of the native and undisturbed soil on either side? For the reason that the soil of the well is quite certain to be finer than the native forest soil, it is evident that the well soil will always contain a higher percentage of moisture. Furthermore, without going into all the details, this question is answered unequivocally by saying that the moisture content, as determined for the well soil, can never be considered as an exact measure of the moisture outside. The well samples will be principally useful in showing changes, and without doubt should occasionally be compared with native samples taken near by. It is believed, however, that for practical purposes a certain constant relation between the two soils may be assumed. So far, because of the great difficulty of actual contact tests between two soils, the moisture ratio at equilibrium must be established on theoretical considerations.

From what is known of capillary movement in soils (116) it would seem that, when the moisture content of two soils is near the saturation point, they will be in equilibrium at moisture values measurable by the amount which either soil can hold against the force of gravity.

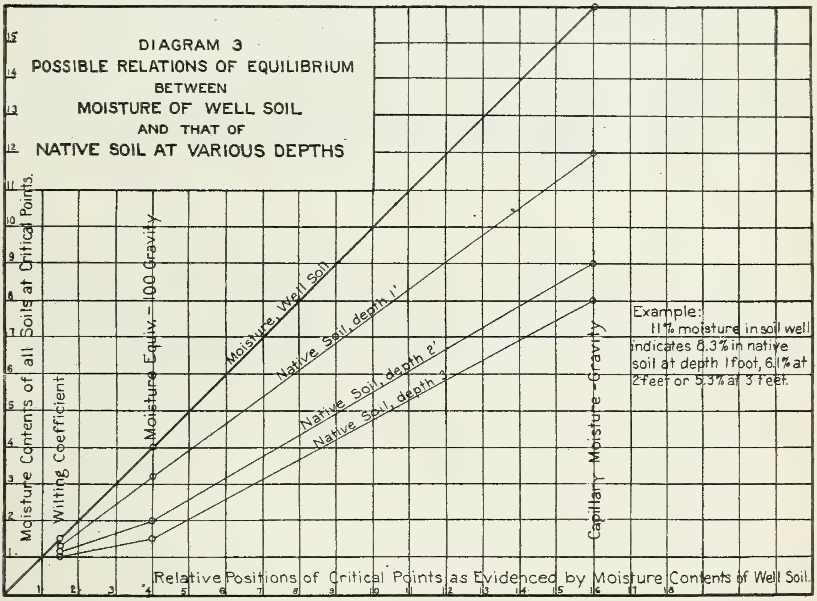


DIAGRAM 3
POSSIBLE RELATIONS OF EQUILIBRIUM
BETWEEN
MOISTURE OF WELL SOIL
AND THAT OF
NATIVE SOIL AT VARIOUS DEPTHS

Similarly, at much lower moisture contents, the amounts which the two soils hold against a force one hundred or one thousand times as great as gravity, would appear to establish a basis for equilibrium. But, in view of the fact that at a low-moisture content actual capillary movement becomes negligible while transfer from one to the other by the vapor-transfer method can be readily accomplished, it seems more logical that we should consider an equilibrium existing which would mean equal osmotic pressures in the two soils. These points can be determined for each soil by freezing-point depressions or by assuming equal osmotic pressures at the wilting coefficients.

Diagram 3 shows a method for working out a scale of relations for the soil of any well and soil from three depths, obtained when the well was dug. The curve for the well soil is a straight line whose ordinates and abscissæ are equal. It need not be drawn at all, except for illustrative purposes. For each of the native soils three or more points may be plotted. The capillarity point has as its ordinate the actual capillarity of this soil; but the abscissa has the value of the capillarity for the well soil, similarly, for the moisture equivalent at 100 gravity (which is still a capillarity measure) and the wilting coefficient, or any other point at which osmotic pressure of the several soils would be in equilibrium. (See also diagrams 8, 9, and 10 and discussion, p. 116.)

These curves may then be used to transpose moisture values for the soil well directly into moisture values for the native soil, realizing the probability which has been mentioned that at any moment the well and native soil may be far from a state of actual equilibrium.

TECHNIQUE OF PERIODIC SAMPLING.

The field work of soil sampling is essentially the same where soil wells are used as where it is feasible to sample the native soil. Soil samples should be taken at permanent stations at least weekly during the open season. Definite depths of 1, 2, and 3 feet, and more if necessary, will recommend themselves in preference to long cores, which show less definitely the location of the moisture. The 1-foot sample may be obtained by a core extending from 10 to 14 inches; the 2-foot, at 22 to 26 inches; and the 3-foot, at 34 to 38 inches. If intermediate values are desired, they may be obtained by interpolation.

Each sample as obtained should be placed in a soil can, the number of which may immediately be entered on a convenient field form,[10] together with the number of the station and the depth. There is an infinite variety of soil cans, but perhaps the most generally serviceable form is a rather heavy, stamped aluminum, screw-top can, about 2¼ inches in diameter and 2½ inches high.

Soil cans containing moist soil must be shielded from the sun and from excessive heat, and should be weighed at the earliest opportunity, the weight being ordinarily determined to the nearest centigram. (Fig. 2.)

Soil samples of any ordinary texture, and of weight not exceeding 100 grams, should be dried for at least eight hours in an oven having the temperature of boiling water. Unusually moist samples, or those of very fine texture, should be given a longer period. Drying for 24 hours is not too long to make good results certain. Especial care must be used with humus soils of low conductivity. Only trial weighing will show when a sample is as dry as possible for the conditions of the oven.

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[10] Forest Service Form 486, fitting notebook cover 874–C.

After drying, each soil can should be immediately covered and weighed.

The moisture percentage should be determined on the basis of dry weight of soil, by deducting the can weight from the dry weight, deducting the dry weight from the wet weight, and dividing the second remainder by the first remainder. Moisture percentages are usually worked out to one or two decimal places.

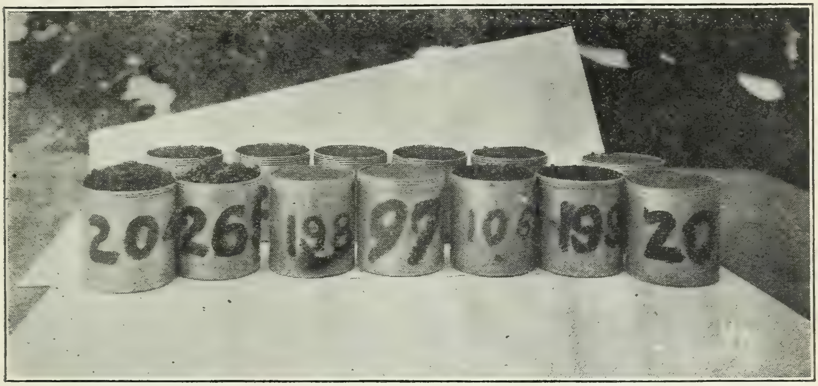


FIG. 2.—Ordinary soil cans, for collection of moisture samples, with covers removed. Size $2\frac{1}{4}$ by $2\frac{1}{2}$ inches.

Soil cans in continuous use should be weighed at least twice each season, preferably at the beginning and middle of their periods of use. Aluminum cans, while satisfactory in most respects, wear appreciably in a few months.

Form 3—D 2.

[United States Department of Agriculture, Forset Service.]

PHYSICAL SURVEY—SOIL MOISTURE.

Type——————; *Station No.* ——; $\left.\begin{matrix}\textit{cover}\\\textit{open}\end{matrix}\right\}$ *mark out one; for the month of*——————, *19*—.

Date.	Depth..................			Depth..................			Depth..................			Depth..................			Depth..................		
	Soil moisture.			Soil moisture.			Soil moisture.			Soil moisture.			Soil moisture.		
	Sample (T1) %.	Ratio.	Native soil %.	Sample (T1) %.	Ratio.	Native soil %.	Sample (T1) %.	Ratio.	Native soil %.	Sample (T1) %.	Ratio.	Native soil %.	Sample (T1) %.	Ratio.	Native soil %.
Sum, month..........															
Mean, month..........															

* COMPUTATIONS OF AVAILABILITY OF SOIL MOISTURE, ETC., FROM DATA GIVEN ABOVE.

Date.															
	**														
Sum, month..........															
Mean, month..........															

* Data on which computations are based..

** Explanation of symbols used in captions..

Prepared by ....

The figures resulting from the above computations for the moisture of the soil in soil wells may be tabulated on the "Soil Moisture" form in the columns headed "Sample. T1." The ratio which has been determined between the moisture of the soil in the well and that of the native soil at same depth, and the computed moisture of the surrounding soil, or the moisture figure read directly from curves, may also be entered for each date. If the native soil moisture is directly determined by sampling, only the third column under each depth will be used. Space is also provided on the "Soil Moisture" form for any computations which it is desired to make, either currently or after obtaining the monthly means; such as, for example, the percentage of available moisture, the availability, or the various percentages on a volume basis. Appropriate headings may be supplied.

DETERMINATION OF NONAVAILABLE MOISTURE.

The method of soil wells does not attempt to standardize soils for different localities, which could only be done thoroughly by using soil from one source in all soil wells. Nor is it desirable that soils of different localities should be compared on the same physical basis, since this physical basis of itself determines quite largely the mean water content of the soil and its attraction for a given species. It is, however, necessary before different sites and localities may be satisfactorily compared as to their soil moisture that it should be known, at least approximately, at what points they become physiologically dry, either for plants in general or for plants of a given species. Briggs and Shantz (114), it is true, after an exhaustive study of this subject which has cleared the way for many other investigations, summarize in part as follows:

> The results of this investigation have led us to conclude that the differences exhibited by plants in this respect are much less than have heretofore been supposed, and are so small as to be of little practical utility from the standpoint of drought resistance. As compared with the great range in the wilting coefficient due to soil texture, the small differences arising from the use of different species of plants in determining the wilting coefficient become almost insignificant.

Expressing this difference numerically, it is said:

> Taking 100 to represent the average wilting coefficient, the different species tested (except *Colocasia* and *Isoetes*) give an extreme range from 92 for Japan rice to 106 for a variety of corn.

From these experiments and conclusions the impression has grown up that all plants are capable of extracting the moisture of the soil to essentially the same basic point. Shantz may be quoted as saying that there was no intent to convey this impression, and experiments to be described later will show that as between tree species adapted to radically different habitats, there may be, at least under certain conditions of wilting, radical differences in the coefficients. Another important phase of the matter is that certain soils may have a peculiar reaction on one species and not on others; as, for example, a highly acid or strongly limey soil. It is therefore the part of wisdom to test the nonavailable moisture of any soil by the use of at least the predominating or type species found on the soil, and of as many other species as possible.

DIRECT DETERMINATION OF THE WILTING COEFFICIENT.

The writers cited above have given such thorough consideration to this and the succeeding subjects that a complete discussion here appears almost useless. The treatment of forest soils and forest species, however, has brought out a number of new problems, so that it is almost impossible to overlook any phase of the question in this discussion. Constant comparison will be made with the treatment found desirable for field crops and related plants.

It is well to bear in mind from the outset the point brought out by Briggs and Shantz that the wilting coefficient represents merely the moisture point at which wilting first occurs to such an extent that the plant does not recover if placed in a saturated atmosphere. The plant may actually draw considerable water from the soil after this, and might be theoretically conceived to pass moisture to the atmosphere until the soil and atmosphere were in vapor-pressure equilibrium. The wilting coefficient is, however, the practical expression for nonavailable moisture.

The fact must also be strongly emphasized that the point at which wilting occurs must depend in a very large measure on the rate at which the plant is transpiring; or, in other words, on atmospheric conditions and sunlight. Therefore, as the soils approach dryness, the conditions should be maintained at a fairly definite standard. It will usually be feasible to prevent the occurrence of temperatures in excess of 70° F., as well as sudden changes in temperature, and to exclude direct sunlight. It would also be desirable to control atmospheric moisture, though this is a very difficult thing to do in ordinary rooms.

In the tests with seedlings of coniferous trees it has been found exceedingly difficult to determine when permanent wilting occurs. There is no doubt that seedlings of this kind have developed a power of resistance, or recovery, far in excess of that of most plants. This probably consists in an extremely low rate of transpiration when the moisture becomes deficient; but the difficulty of observation may be mainly ascribed to the fact that the stems, and to a lesser extent the leaves, become stiff and woody at a very early age, so that shriveling rather than collapse is the phenomenon that evidences lack of water in the aerial portions. This is particularly true of yellow pine and Douglas fir seedlings, at the age of six weeks or more, while lodgepole pine does not harden until much later.

For these reasons wilting can rarely be recorded in a large number of seedlings simultaneously, and it is therefore desirable that the moisture content should be recorded as each seedling wilts, an algebraic mean content being computed when the process is complete.

While Briggs and Shantz found it desirable to grow the seedlings in small glass pots (these seem to have had about the dimensions of drinking glasses), the heterogeneous character of nearly all forest soils necessitates the treatment of samples large enough to include a normal proportion of rock fragments. If these are very large they may be broken down to maximum dimensions of about 2 inches without appreciable alteration of their relations to moisture, but that is all that can be done. These rocks can not be eliminated altogether, as it is found that the more permeable of them may hold 1 to 2 per cent of nonavailable moisture. They are distinctly a part of the soil and it is their presence which, in a large measure, makes the soil capable of supporting forest growth.

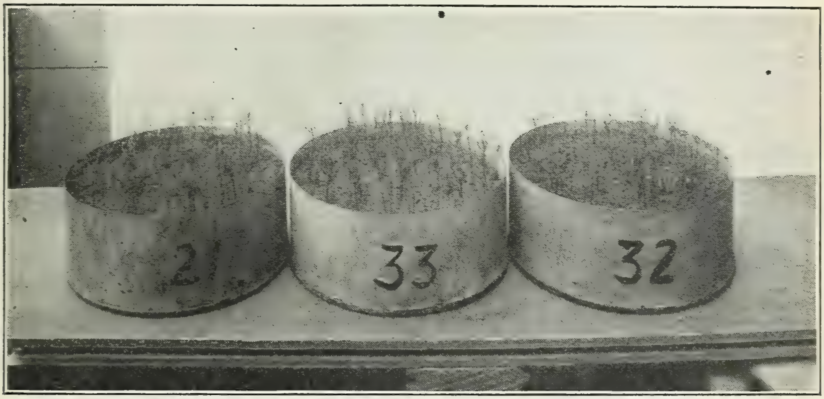


FIG. 3.—Echard pans, 7 by 3 inches, containing seedlings.

A pan (fig. 3) which meets these requirements is made of 20-gauge or 24-gauge galvanized iron, 3 inches deep and 7 inches in diameter. Half a dozen small perforations in the flat bottom permit drainage while the seedlings are being started, and aeration after the surface of the soil has been sealed over. When filled to a depth of 2½ inches, such pans hold 3 to 6 pounds of soil.

To avoid any chemical change in the soil, but more particularly to keep it receptive toward moisture, the dry weight of soil placed in the pan is determined rather by moisture samples secured as the pan is being filled than by drying the whole mass. The latter, moreover, is a slow process, especially with soils of low conductivity.

However, no bad effects whatever have been noted from drying fairly sandy soils at the standard temperature.

After obtaining the air-dry weight of the pan and soil, an amount is removed from the pan sufficient to form a layer one-fourth of an inch deep. The coarser material is excluded from this lot, which is to form a covering for the seeds. With this taken out, the remaining soil is leveled down with a spoon, the seeds are sown on this smooth surface, and the covering soil is replaced.

The number of seeds to be sown should be gauged according to known viability, so as to produce about 100 seedlings in a pan of this size. The weight of the seeds is obtained before sowing, and this weight is considered throughout as an addition to the tare. The further assumption is made that the weight of the seedlings will not at any time appreciably exceed the weight of the seeds.

Having calculated the net dry weight of the soil from the moisture content of the dried sample, the moisture content of the soil at any stage in development or wilting of the plants is calculated, after a weighing of the pan, by the equation:

$$\text{Moisture percentage equals } 100 \times \frac{W-(\text{Pan, seed, soil, and paraffin})}{\text{Soil}}.$$

The pans are placed in a greenhouse where they may have the necessary light and warmth to induce prompt germination, and for the sake of uniform development and conditions affecting wilting, are preferably kept on a revolving table.

The soils are watered exclusively with distilled water, both to avoid the introduction of spores and the addition of salts, which, in the absence of drainage, might appreciably increase the wilting coefficient. Nothing suggestive of a toxic effect from this distilled water has been noted. It is desirable to aerate the water as much as possible before applying. Under ordinary atmospheric conditions, the pans will require 50 to 60 cubic centimeters per day to maintain moisture favorable for germination.

In working with deeper mineral soils, damping off of seedlings is rarely noted, but surface soils from the forest often contain the damping-off fungi. In fact, this is so common that many observations which ascribed the death of seedlings in the forest to unfavorable physical conditions may be questioned. Certain it is that damping off in the wilting pans may cause the greatest confusion, if they do not actually vitiate the tests. Soils suspected of containing these organisms should therefore be treated, several days before the seed is sown, with a solution of formaldehyde, as suggested by Hartley (124) for nursery beds. This should be used at the rate of about one-eighth of a fluid ounce per pan, dissolved in sufficient clean water to reach all soil in the pan. Opportunity should afterwards be given for the formaldehyde to evaporate entirely. This will doubtless occur before the soil is perfectly dry.

When germination is fairly complete, the seedlings well established so as to reach all parts of the soil, and the tendency to succumb to damping off, if any, outgrown, the surfaces of the pans are sealed over by pouring on the top of the soil, previously leveled, about 50 grams of a melted mixture of paraffin and petrolatum (veterinary vaseline is one of the least expensive forms) in the proportion of 2:1. This congeals at 40° C. and may be applied at 50° C. without any injury to the stems of the seedlings. Not infrequently, if the wilting process requires many days, the seal will draw away from the edges of the pan, but this is easily rectified by the use of a blunt, smooth stick. At any rate, it is not essential absolutely to prevent direct evaporation from the soil, though a more even distribution of moisture may be expected if such loss is kept at a minimum.

The weight of paraffin added is determined by weighing the beaker from which it is poured before and after each application. This makes a further addition to the tare. The soil should be fairly moist when the paraffin is applied, so that the latter will not penetrate.

With coniferous seedlings, provided a good stand has been secured, the withdrawal of moisture and the sealing of the pans may usually be undertaken at four to six weeks after sowing; though in the case of spruce and perhaps other species which root rather slowly a slightly longer perior may be desirable. As has been pointed out, the difficulty of detecting wilting increases as the seedlings become older and more completely lignified. It is also unmistakably true that the older the seedling the more difficult it is to kill. This is probably due in part to greater resistance to drying out and in part to deeper or more extensive rooting, which would be an advantage if the moisture at, say, the bottom of the pan, were not being drawn on as freely as that near the surface. However, observations on the wilting of seedlings under direct insolation point unmistakably to resistance increasing with age. When the surface of the soil becomes extremely warm, even if there is an abundance of moisture within reach of the roots, wilting is likely to be evidenced by collapse of the stem at the ground line. The phenomenon is almost identical when the surface of the soil becomes dry in advance of the deeper soil. The seedling is undoubtedly vulnerable to water loss and critical injury in the lower part of the stem. Under such conditions it is noted that the younger seedlings usually succumb first, and those which survive one exposure are killed by a repetition which is still more severe.

It is evident, therefore, that age of seedlings will have an important influence on the results, though this will not be so important if the test is conducted in such manner as to keep the moisture uniform throughout the soil, and hence uniform for the deepest and shallowest-rooted seedlings.

It is also self-evident that specific differences may be brought out by one set of conditions, which would not be apparent in another set, particularly conditions which make the requirement for moisture great or small. If transpiration is very rapid, seedlings of a shallow-rooted species may be unable to meet this demand, while deeper-rooted seedlings in the same pan may pull through, because their supply at this stage is somewhat more readily obtained. For an actual test of drought resistance, therefore, it is fundamentally necessary that the transpiration and soil-drying process should be slow enough to permit equalization of the opportunities before the critical test comes. Hence the standard conditions of exposure which have already been suggested.

The method of recording the death of each seedling in a lot of 100, together with the pan weight and calculated moisture accompanying such death, has a distinct advantage over the method which permits only one determination of the moisture content when all of the seedlings, or a majority of them, have succumbed. It gives an indication of the possible variation between individuals of the same species, and a measure of the probable experimental error due both to this variation and to uneven distribution of moisture in the pan, which is not wholly avoidable. What it really amounts to is practically 100 separate tests on 100 sections of soil. If, on the one hand, the first losses occur in sections of the soil which have unavoidably become drier than the average, on the other hand, the last survivors are undoubtedly in areas which are at the opposite extreme. These variations should be largely compensated by taking the algebraic mean of all the moisture determinations, a figure in which a great deal of confidence can be placed.

INDIRECT METHODS FOR WILTING COEFFICIENTS.

Inasmuch as the direct determination of the wilting coefficient is a process which is likely to require several weeks, at the best is liable to rather large experimental errors, and is also, without question, influenced by the kind of plant used, various methods have been developed by which the affinity of the soil for water may be determined; and the amount of water held by it under certain empiric conditions of the test may be related to the amount which would be held against the pull of plants.

In addition to furnishing a ready, if only approximate, index to the soil conditions which may be encountered in the field, and especially an index to the danger of early drought, it seems that the use of indirect methods, employing definite physical forces for the creation of a certain condition of soil moisture, has a scientific value which fully justifies an elaborate description of them. For example, such methods permit us to compare the drought resistance of any number of species in any number of soils through any period, provided only that the experimental conditions are reproducible. We can determine this relative drought resistance, as between two or three species, by wilting them simultaneously in the same soil mass, and gradually, by one comparison and another, include all of our species and all of our soils. Even this method, however, is not free from the necessity for uniform conditions in the successive tests. It is therefore best that each wilting coefficient, while being determined under some arbitrary and standard set of conditions, should be related to some other measure of the soils' water-holding capacity which, under reproducible test conditions, always means just one thing. In this way an enormous number of comparisons may be made between the wilting coefficients for different soils and different species. Such physical determinations may also lead to a critical examination of wilting coefficients and to the most desirable standard methods for their determination.

Of the various indirect methods which have been devised may be mentioned:

1. The determination of the antiosmotic pressure of the soil, corresponding to the maximum osmotic pressure which the species under consideration is known to tolerate without fatal results. This method is obviously not so useful as the others, since it presupposes some knowledge of the plants which may not be available. It must necessarily consist of a number of determinations on the same kind of soil, at different moisture contents, until the moisture condition is found at which the freezing point becomes "submerged;" that is, becomes indeterminate. Obviously, this leads to the region in which the freezing-point determinations are least precise. While not abandoned, this method will be laid aside to be discussed more fully, and in its most useful aspects, in connection with the coefficient of availability.

2. The capillary moisture determination, in which the soil is allowed to demonstrate its ability to hold water against the force of gravity.

3. The moisture-equivalent determination, in which the moisture in the soil is subjected to any definite force, dependent on its own mass. This may be a force one hundred or one thousand times as great as gravity created by the centrifugal method.

4. The hygroscopic coefficient determination, in which the affinity of the soil for moisture is determined by exposing it to an atmosphere of saturated vapor.

The *capillary moisture*, or "capillarity," the terms being used interchangeably, in this discussion, refers to the quantity of water that may be held by the soil against the force of gravity. This amount decreases as the height of the column of soil increases, and may also be considerably influenced by the packing of the soil. Since it is almost impossible to treat any soil in the same state of compactness in which it is found in the field, or to establish a standard condition for soils in vessels, this measure of the water-holding power of a soil is not likely to have precise value. The greatest theoretical objection to it is, that the force tending to remove the water from the soil is of an entirely different magnitude from that at work as the plant makes its final struggle for water, and that the effect produced by the one force can not serve as a measure of the effect which might be produced by the other. There seems also to be an impression that salts in the soil water operate to raise the wilting coefficient, while decreasing the capillary moisture by lowering the surface tension of the liquid. Such an impression arises from the well-known effect of foreign substances on the surface of a liquid. It has been pointed out by Free (121) that salts in solution actually increase the surface tension of the liquid, and this is entirely in keeping with the known properties of solutions. While the presence of solutes may have the effect of weakening the affinity of one water molecule for another, this is fully counterbalanced, in its relation to capillarity, by the greater density of each group of molecules of which the solute forms a nucleus, and the consequent greater affinity between such groups and the solid surface. This affinity is known by the name of "capillary attraction." Furthermore, even while admitting that in either the capillary moisture test or the moisture equivalent test some of the solutes may be lost with the water which is drained out of the soil, considerable satisfaction is gained from the idea previously set forth that, at the wilting point of soils, these solutes may be absorbed by the colloids.

It is believed that Hilgard (125) was the first to employ the principle of capillarity for comparing soils. He used a sieve cylinder only 1 centimeter high, which, after a layer of filter paper was placed in the bottom, was filled level with the soil. This was immersed to a depth of 1 millimeter in distilled water, allowed to stand for an hour, and then weighed. The amount of water absorbed, of course, was dependent on the ability of the soil to lift it, a maximum distance of 9 millimeters.

Briggs and Shantz (114) compared this measure of absorbing capacity with the directly determined wilting coefficients of 15 soils whose wilting coefficients ranged from 0.9 to 16.7 per cent. From these comparisons it is evident that a soil which is able to withhold almost no moisture from plants has a fairly high capillarity, but that the latter does not increase in so great a proportion as the wilting coefficient with more retentive soils. Thus it was necessary to subtract 21 from the percentage of capillary moisture to obtain a quantity having a fairly constant ratio to the wilting coefficient.

This is given by $\frac{\text{Capillarity}-21}{\text{Wilting Coeff.}}=2.90\pm0.06$, or± 2.01 per cent.

The probable error of a single determination by this means was found to be 8.3 per cent of the wilting coefficient.

In the treatment of forest soils Bates (105), at the Fremont Experiment Station, has found it necessary to use much larger cans than those employed by Hilgard, and has also reversed the process, so that the result is rather a measure of the ability of the soil to hold the water of saturation than to lift water from below. A galvanized can 5½ inches deep and 4 inches in diameter, is filled to a depth of 5 inches with air-dried soil, which is jarred and tamped until no appreciable settling occurs. This can is perforated in the bottom and a filter paper is used to keep the soil from sifting out. The can is immersed to its full depth in water, but no water is allowed to flow on the top of the soil. As the water rises from the bottom by its own pressure, the air is pushed out, so that few, if any, air spaces are left. The samples are allowed to soak at least 24 hours to insure complete absorption by the larger, permeable rock fragments.

The weight attained at the end of this period, or a longer period if it appears necessary, is an index to the saturation capacity.

The cans are now placed on a drain board, covered, and allowed to stand for 48 hours. In rehandling the cans care must be used to avoid jarring, as some of the water is held in a very delicate balance. The amount of water held at this time is a measure of the capillary moisture. In the vast majority of soils that have been treated, the capillary moisture is about 90 per cent of the saturation capacity. Clay does not affect this ratio appreciably, but humus increases it.

The same cans are now used for the centrifugal test or moisture equivalent determination, which will shortly be described. After this they are oven-dried, to give the basis for dry-weight calculations. The apparent density is also computed from the weight and volume after this treatment.

In Table 2, there is presented a comparison of the capillary moistures and wilting coefficients of 10 soils of one general type (granitic) from an Engelmann spruce forest, but varying widely in state of decomposition, clay content, and humus content. Each soil represents a sample extending from the surface to a depth of 1 foot. The wilting coefficients for Douglas fir and Engelmann spruce were most carefully determined, the only objection that might be brought against the treatment being that the seedlings were given more direct light than now seems desirable, although not enough to develop excessive temperatures. In contrast, there are also presented the results of nine tests on coarse granitic gravels, from depths of 1 to 3 feet, containing minimum amounts of humus and clay. The wilting coefficients were determined in the same manner as the other group, and at almost the same time.

TABLE 2.—*Capillary moisture, moisture equivalent, and wilting coefficient of 19 soils. (Wilting coefficients determined synchronously.)*

Sample No.	Capillary moisture (G).	Moisture equivalent (100-G).	Mean wilting coefficient (spruce and fir).[1]	Humus by ignition.	Clay.	Water[2] soluble matter.	Ratio mean wilting coefficient.		Final[3] wilting coefficient.	Ratio final wilting coefficient.	
							To capillarity.	To moisture equivalent.		To capillarity.	To moisture equivalent.
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Parts per million.*			*Per cent.*		
539	17.07	11.68	3.17	3.29	4.5	305	0.186	0.271	2.56	0.150	0.219
555	20.29	11.72	3.00	3.52	0.4	275	.148	.256	2.52	.124	.215
534	24.06	14.45	3.90	3.00	2.2	465	.162	.270	3.30	.137	.228
547	29.34	20.32	6.01	6.56	6.7	270	.205	.295	5.26	.179	.259
545	33.77	22.02	6.02	7.09	3.6	845	.178	.273	5.18	.153	.235
549	36.16	19.95	7.04	6.04	4.2	555	.195	.353	6.10	.169	.306
544	41.56	26.30	8.68	11.64	3.4	1,030	.209	.330	7.83	.188	.298
526	49.92	29.84	8.60	9.75	3.2	530	.172	.288	6.95	.139	.233
546	60.00	42.72	20.46	21.10	2.6	200	.341	.479	11.17	.186	.262
538	89.05	73.50	21.71	27.00	2.7	1,250	.244	.295	13.89	.156	.189
Group averages, granitic loams							.204	.311	....	.158	.244
292	11.02	5.04	2.73	1.02	1.5	700	.248	.542	1.79	.162	.355
37	11.46	3.53	2.00	1.35	0.2	500	.174	.567	1.18	.103	.334
235	12.00	5.06	3.09	2.09	3.1	800	.257	.611	2.25	.188	.445
36	12.95	4.35	2.47	1.74	2.7	500	.191	.568	1.64	.127	.377
293	12.96	5.62	2.93	1.79	1.5	200	.226	.521	2.06	.159	.367
82	13.18	4.86	2.27	1.85	1.9	600	.172	.467	1.85	.140	.381
83	13.61	5.19	2.76	1.76	2.5	500	.203	.532	1.76	.129	.339
85	15.30	5.57	2.54	1.92	2.1	800	.166	.456	1.62	.106	.291
84	15.65	5.03	2.54	1.31	3.7	800	.162	.506	1.62	.104	.322
Group averages, granitic gravels							.200	.530	....	.135	.357
Grand averages							.202	.415	....	.147	.298
Mean variation of single values							.0333	.1157	....	.0228	.0607
Percentage of mean variation							16.5	35.9	....	15.5	20.4
Probable error in average							.0066	.0230	....	.0045	.0121

[1] In these tests spruce and fir gave almost the same figures, on the average.
[2] 200 grams soil leached on filter, with 1 liter water, through 24-hour period. For the gravel group results are approximations, on account of lack of sensitive scale.
[3] Average of the moistures existing for last tree of each species.

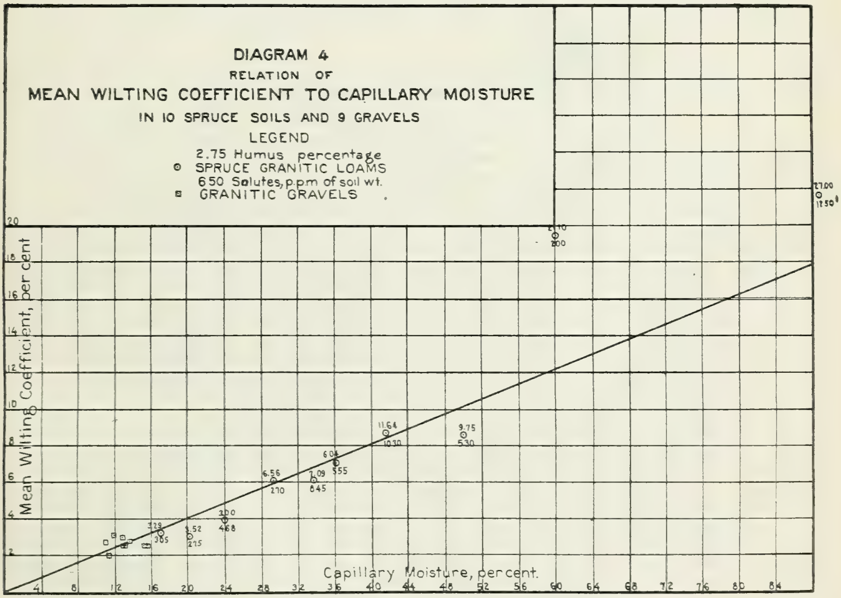
To avoid duplication of tables later there are also inserted here the moisture equivalents of the same soils.

The comparison of capillary moisture and wilting coefficients given in Table 2 brings out the following facts:

1. An examination of the column headed "Ratio of mean wilting coefficient to capillarity" shows that there is considerable variation in the individual results. In the first group the two results which are appreciably higher than the average are those for samples of the highest capillarity, resulting from unusual quantities of humus.

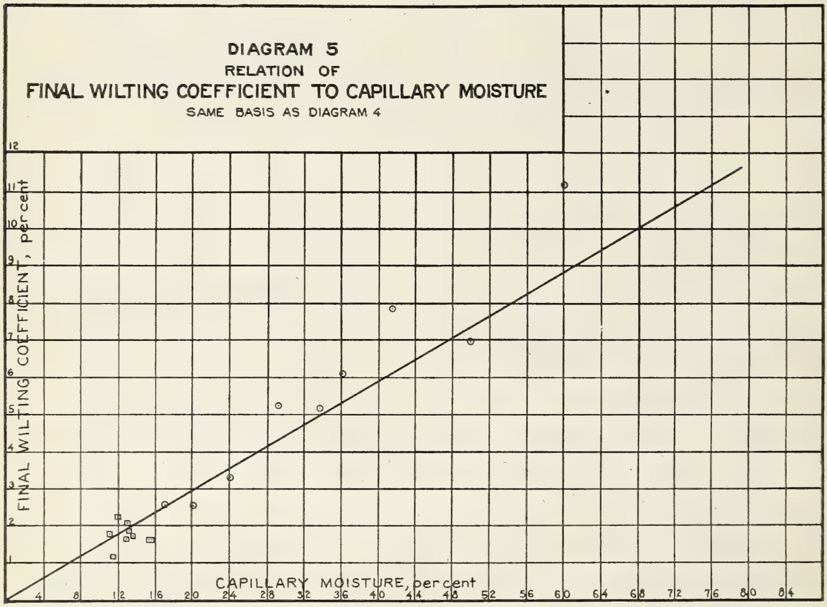
2. The group averages for the loamy spruce soils and the granitic gravels are essentially the same. It therefore seems entirely legitimate to consider both groups together and, as shown in diagram 4, to express the relation of wilting coefficient to capillarity by a straight line. The nineteen cases show an average variation of 0.0333 from the mean ratio of 0.202, or 16.5 per cent variation.

3. Both from its mean value and from the fact that the graph which expresses this relationship passes through the main axis of the system of coordinates it is evident that the capillary moisture as it has been measured by the method described above is an entirely different expression from that used by Hilgard and by Briggs and Shantz.



4. The relatively high wilting coefficients of the loamy soils having the largest humus contents are believed to result from experimental errors, largely unavoidable, and due to the lack of capillary conductivity in soils which are particularly loose. This lack permits a seedling to succumb in one region of the soil, while there may be considerable free moisture elsewhere. The two gravelly soils which show similarly high wilting coefficients also have high moisture equivalents, and it is thought from this that they were probably richer than usual in permeable feldspar, which could not hold much water but would probably hold it very firmly.

5. It is to be noted that the percentage of variation of individual cases is slightly less when the final (diagram 5) rather than the mean wilting coefficient of each soil is taken. On the other hand, there is considerably more spread between the two groups on this basis. It is believed that the slightly poorer showing made by using the mean wilting coefficient is due to the fact that losses caused primarily by fungi were not entirely eliminated from the calculations. With care in this respect, the mean value for all the seedlings is undoubtedly the more dependable and also more expressive. It should be noted in this connection that in a group of 100 seedlings the weakest usually give a wilting coefficient twice as high as that indicated by the final wilting, and not infrequently three times as high.



6. The comparison of wilting coefficients with moisture equivalents shows a wide gap between the two groups. The value of the moisture equivalent data will be discussed later.

7. While these results, all obtained at practically the same time and in soils which showed no great chemical activity, indicate a useful parallelism between wilting coefficient and capillary moisture, it should be pointed out that the wilting coefficient may occasionally go out of bounds as the result of acidity or alkalinity, so that any of the physical tests on soils, taken alone, are quite worthless. It should not be surprising to obtain wilting coefficients twice as great, relative to capillarity, as those indicated above, especially with the pines.

It is desired to present another set of data obtained by Bates (105) to illustrate the need of establishing the wilting coefficient for the particular species in which one may be interested and, therefore, of establishing a specific relationship between the wilting coefficients and the capillary moistures of the same soils. This presentation also assists in showing, what has already been mentioned, that a measure of the capillarity or other moisture relation of the soil has an indirect value in permitting comparisons of the species under a variety of conditions.

The tests as represented in Table 3 were performed on five distinct kinds of soil, varying as to origin (hence, chemically) and also considerably as to composition and water-holding capacity. With the exception of the prairie soil, which contained only 1 per cent of coarse sand and no gravel at all, these soils were prepared by passing through a sieve with quarter-inch meshes.

The wilting coefficient determinations, moreover, were made without the use of paraffin. As the test was designed particularly to compare the four species which were grown in each soil, and it had become apparent that the rooting habit of each had a good deal of bearing on the stage in soil drying at which it succumbed, the effort was made to keep the upper layer of the soil well supplied with moisture by daily watering. As a result, the common drying of the steam just at the ground line was not appreciably in evidence and, indeed, so general was the drying that the determination of the end point was exceedingly difficult. It was based almost wholly on the flaccidity of the leaves. Whether because of this protection afforded the stems by surface watering, or because of the comparative shade in which the end points were approached, it is noteworthy that the ratios of wilting coefficients to capillarities are much lower, except for the heaviest clay, than in the results obtained under different conditions and already described.

Another noteworthy feature of this test is that the seedlings were produced in each soil with the moisture brought daily to the moisture equivalent, so that the availability was, as nearly as could then be calculated, the same in all cases. When drying began, each soil was brought by easy stages to two-thirds of the moisture equivalent, and finally to one-third. The seedlings attained an age about 6 months before the test was completed.

TABLE 3.—*Wilting coefficients of four species in five types of soil.*

Sample No. and description.	Capillary moisture.	Moisture equivalent 100-G.	Mean wilting coefficient.			
			Yellow pine.	Lodgepole.	Douglas fir.	English spruce.
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
590. Sifted granite gravel with loam	26.58	10.55	2.50	2.79	2.60	2.72
604. Composite limestone	31.85	22.00	3.82	4.74	4.06	4.03
602. Composite sandstone	35.34	21.77	5.01	6.30	5.08	4.87
601. Prairie soil from shale	37.77	28.79	8.65	9.65	8.52	8.76
603. Composite lava	43.16	27.80	5.56	7.48	5.44	5.31
Averages			5.11	6.19	5.14	5.14

Sample No. and description.	Ratio wilting coefficient to capillary moisture.					Fine material.	
	Yellow pine.	Lodgepole.	Douglas fir.	Spruce.	All.	Silt.	Clay.
						Per cent.	*Per cent.*
590. Sifted granite gravel with loam	0.094	0.105	0.098	0.102	0.100	13.5	5.4
604. Composite limestone	.120	.149	.128	.127	.131	45.8	11.4
602. Composite sandstone	.142	.178	.144	.138	.150	41.8	11.0
601. Prairie soil from shale	.229	.256	.226	.232	.236	53.3	17.2
603. Composite lava	.129	.174	.126	.123	.138	51.9	11.1
Averages	.1428	.1724	.1444	.1444	.151		
Mean variations of single determinations	.0346	.0364	.0324	.0348	.0389		
Percentage of mean variations	24.2	21.1	22.4	24.1	25.8		

Sample No. and description.	Ratio of wilting coefficient to moisture equivalent.			
	Yellow pine.	Lodgepole.	Douglas fir.	Spruce.
590. Sifted granite gravel with loam	0.237	0.265	0.247	0.258
604. Composite limestone	.174	.215	.185	.183
602. Composite sandstone	.230	.290	.233	.224
601. Prairie soil from shale	.301	.335	.296	.305
603. Composite lava	.200	.269	.196	.191
Averages	.2304	.2748	.2314	.2322
Mean variation of single determinations	.0328	.0302	.0328	.0394
Percentage of mean variations	14.2	11.0	14.2	17.0

The wilting coefficient tests given in Table 3 bring out the following facts:

1. The line showing the percentage of the mean variations indicates that the four species taken together and comprising 20 cases have a larger variation from an established mean ratio than any of the individual species. Lodgepole pine shows the highest relative wilting coefficient, and, since the other three species gave almost identical results, it follows that a ratio established by the promiscuous use of species would be most largely in error when applied to calculations for lodgepole.

2. The relatively high wilting coefficient for lodgepole pine has been thoroughly established by numbers of other tests, which, how-

ever, are not given here because the results do not coordinate closely with this set.

3. It is noteworthy that the coefficients for all species in the limestone soil are relatively low, while the really high values are given by the heaviest clay. The latter fact, like the result in a strongly humous soil, is believed to be due to nonconductivity of the clay.

4. In this case the correlation between wilting coefficients and moisture equivalent is a great deal better than the correlation with capillary moisture. In view of what has been said regarding the level of moisture maintained in each pan, it seems pointed to suggest that the wilting coefficient may depend in some measure on the degree of moisture to which the seedlings have become accustomed. It is only logical to suppose that, if abundant moisture tends to stimulate growth, the seedling may, when drought occurs, be relatively deficient in the carbohydrates which assist in osmosis.

The moisture equivalent is a term devised by Briggs and McLane (113) to define the amount of water held by a soil against a definite external force. In the original experiments of these authors the force employed was a centrifugal force exerting a pull 3,000 times as great as the force of gravity. The small samples of soil were placed in finely perforated cans, which in turn were placed against the inside wall of a heavy cylinder. The latter was caused to rotate rapidly by direct connection with a motor.

In this early work the writers seem to have made no attempt to correlate the moisture equivalents with wilting coefficients. There was, however, a fairly successful formula devised by which the holding power of the soil was related to the constitution thereof, as shown by mechanical analyses. This, it is believed, has been found of little use.

It remained for Briggs and Shantz (114) to carry on the wilting tests which showed the real value of the moisture equivalent determinations. In these later tests the centrifugal machine was considerably improved and its speed automatically controlled, while being cut down to give a pull of 1,000-gravity, since it was found that the higher tension extracted relatively little additional water. As the result of some hundreds of wilting tests and comparisons with the moisture equivalents of the same soils, it was found that from light sands to the heavier clays a linear relation exists between these two measures, which is expressed by the formula:

$$\text{Wilting coefficient} = \frac{\text{moisture equivalent}}{1.84\,(1 \pm 0.007)}$$

Or, in other words, there is a probable error of less than 1 per cent in this average relationship. Single determinations, however, show a probable variation of 2.9 per cent of the wilting coefficient, as measured by this direct means.

This work, though extremely thorough, was confined wholly to soils encountered in agricultural regions, and while these varied between 1.6 to 57 per cent moisture equivalent, they were undoubtedly more homogenous than forest soils in general, and lacked the complicating features of both rocks and large quantities of organic matter. It is not desired to suggest that, if this method were readily applicable to forest soils, and if experimental error both in wilting coefficient and moisture equivalent determination could be largely eliminated, the general relationship would be found different in the case of forest soils. Unfortunately, no one has made sufficient use of the moisture equivalent, in connection with wilting tests on forest species and forest soils, to determine whether the formula of Briggs and Shantz holds good. It is hardly to be doubted, however, that a formula must be worked out for each species, or the species of each general climatic region. Also, there is little doubt that occasional soils will be found in which, owing to exceptional alkalinity or acidity, the wilting coefficient is extremely high, and hence the formula breaks down.

In connection with the capillary moisture determinations by Bates (105), data on corresponding moisture equivalents have also been given in Tables 2 and 3. These, as pointed out, were determined on samples which had just passed through the capillarity tests. The 4 by 5½ inch soil cans were placed in a machine of such speed and radius as to develop a centrifugal force of 100-gravity, the radius being computed to the center of the 5-inch column of soil. Ordinarily, 30 minutes of revolution suffices to extract the free water susceptible to this force, but with a heavy clay an hour may be required.[11]

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[11] In order to show the importance of the time element, where such large masses of soil are being treated, and also to illustrate the very great difference between the water-holding powers of sand and clay, two samples were weighed repeatedly after short periods on the centrifugal machine The one sample consisted of very fine, thoroughly washed sand from granitic soils, the other entirely of silt and clay from innumerable sources, the clay probably not constituting over one-fourth of the whole mass. Both samples had previously been compacted by centrifuging, so that the rapid loss of moisture in the first period can not be ascribed to loose structure. The test was somewhat complicated by a freezing atmosphere which, in fact, necessitated cessation before an end point for either soil was plainly reached. From a mass of soil of about 1,070 grams in either case, the sand gave up in 80 minutes 276.3 grams of water, of which 230.7 grams (84 per cent) was released in the first 2½ minutes of centrifuging. The corresponding figures for the silt and clay were 76.2 grams, and 12.7 grams or 17 per cent. In the last 20 minutes of the 80-minute period the loss for the sand was 3.1 grams and for the clay 12.8 grams.

The results of tests so made confirm the idea which was given by Table 2, namely, that the relation of the moisture equivalent, as determined by a force of 100-gravity, to the wilting coefficient, may depend a great deal on the type of soil. To make the reason for this clearer, the data of Table 2 have been further grouped in Table 4, while diagram 6 assists in visualizing the relations. Data for other types of soil have also been introduced. In the case of the sands and the prairie clay, the conditions under which the wilting coefficients were determined were perhaps conducive to slightly lower values than in the other groups. This, however, will affect the comparisons of wilting coefficients with capillary moisture and moisture equivalents, about equally.

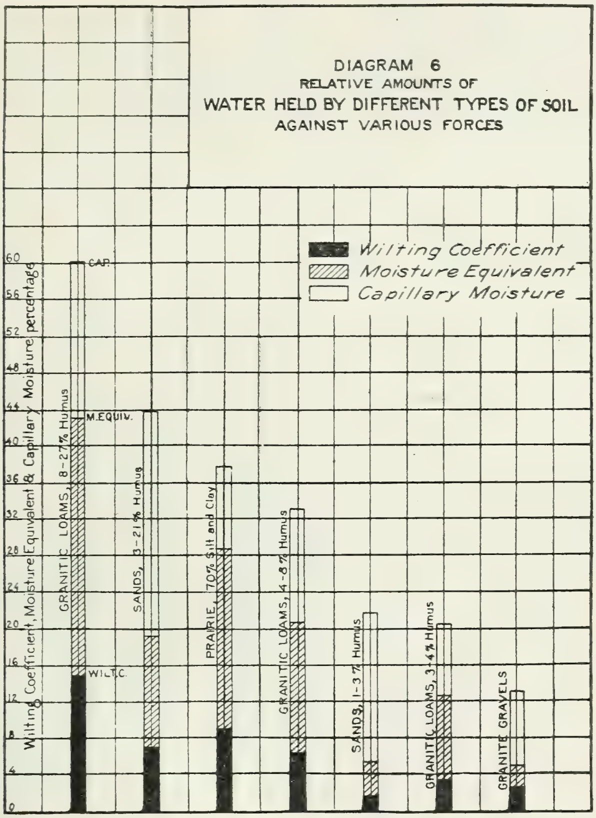

TABLE 4.—*Moisture equivalents in several types of soil in relation to capillary moisture and wilting coefficients.*

Description of group.	Mean capillary moisture.	Mean moisture equivalent.	Mean wilting coefficient.	Mean ratio M.E./C.	Mean variation.	Mean ratio W.C./M.E.	Mean variation.	Mean ratio W.C./C.	Mean variation within group.
	P. ct.	*P. ct.*	*P. ct.*						
9 Michigan and Nebraska sands; humus not over 3 per cent	21.82	5.49	1.73	0.253	0.055	0.320	0.035	0.080	0.016
5 Michigan and Nebraska sands; humus 3 per cent to 21 per cent	43.78	19.24	6.99	.407	.090	.357	.028	.152	.023
9 Pikes Peak gravels; humus 2.1 per cent, clay 3.7 per cent (maximum)	13.13	4.92	2.58	.377	.040	.530	.038	.200	.030
3 granitic loams (spruce); 3 to 4 per cent humus	20.47	12.62	3.36	.621	.042	.266	.006	.165	.014
3 granitic loams (spruce); 4 to 8 per cent humus	33.09	20.76	6.36	.632	.054	.307	.030	.193	.010
4 granitic loams (spruce); 8 to 27 per cent humus	60.13	43.09	14.86	.692	.077	.348	.066	.242	.051
1 prairie clay; 70 per cent silt and clay, very little humus	37.77	28.79	8.90	.762	....	.310	....	.236	....
Average of groups	....	....	....	.533	....	.348	.034	.181	.021
Mean variation between groups	....	....	....	.1624	....	.0543	....	.0419	....

1. There are three outstanding facts in connection with these data, clearly shown by the diagram. The first of these is that the two groups of sands show an extremely large proportion of the capillary water removable by the force of 100-gravity, and correspondingly low wilting coefficients. This speaks for the light hold which the sands have on their moisture, when even approaching saturation.

2. The second conspicuous fact is that, with the exception of the granitic gravels, the wilting coefficients and moisture equivalents rise and fall somewhat proportionately. The gravels have the smallest capacity for capillary water, a very weak hold on a large part of it, and a strong hold on the remainder. This is partly caused by a small quantity of clay derived from the feldspar, but more largely to the fact that the feldspar is itself somewhat permeable. Coarse cleaned gravel of this type has been shown to have a capillarity of only 2.90 per cent, but a moisture equivalent of 1.70 per cent. It seems likely that practically all of the latter would be non-available.

3. Another important point to be noted is the very small amount of water removable from the prairie clay by the moderate centrifugal force, and the correspondingly high wilting coefficient.

4. Finally, although the influence of humus is somewhat obscured by the fact that increasing amounts of it in one general soil type are usually accompanied by increasing amounts of silt and clay, it seems fairly certain that the humus does not yield up its moisture any too readily and that it may tend to make the wilting coefficient relatively high by preventing capillary movement to the roots. It must also

be remembered that, while the table indicates three times as much water-holding capacity in the granitic loam of high humus content, the actual increase over the same type of soil with little humus is only about 65 per cent on a volume basis.

The sum of these various effects of different soil properties on the moisture-holding properties is shown in the final line of Table 4, where it is clearly indicated that there is a closer parallelism between wilting coefficients and moisture equivalents than between wilting coefficients and capillarity. Eliminating the granitic gravels, the average variation of the group ratios is only 7.5 per cent from a mean value W. C./M. E. of 0.318. The explanations given, moreover, all tend to confirm the belief that the moisture equivalent obtained with a much greater centrifugal force would give a still closer index to the wilting coefficient of any of these types of soil.

The *hygroscopic coefficient* is an expression of the amount of water held by a soil after a limited exposure to saturated water vapor under certain conditions. As in the case of the capillary moisture measure, it appears that Hilgard was the first to make practical use of the absorption powers of soils, to compare them generally as to physical properties, and to obtain an approximate measure of their wilting coefficients. More recently Alway (102, 103) has done a large amount of work on this subject, using Hilgard's methods very largely, but also investigating many possible sources of error in the routine treatment of samples.

It is a very well-known fact that a soil is never entirely devoid of moisture if dried in the air for an indefinite period. On the contrary, if atmospheric conditions did not fluctuate so rapidly there would be at all times an amount of moisture in the soil somewhat proportionate to the amount of vapor in the atmosphere. The amount so held is a measure of the soil's hygroscopicity, but not a useful measure because of the changing conditions of the atmosphere.

Similarly a soil undoubtedly still possesses some hygroscopic moisture when dried in an oven at, say, 100° or 110° C. The only way in which the soil can eventually be robbed of all its moisture is by drying in a vacuum, by means of which the constant withdrawal of the atmospheric vapor is assured. For practical purposes, however, drying in an ordinary atmosphere at 110° C. gives a good basis for moisture calculations, since at that temperature the vapor in the atmosphere will be very much rarefied in comparison with its saturation capacity. This point is mentioned because it is not infrequently noted, in drying large samples, that they may gain moisture in the hot-air oven if there is a decided increase in atmospheric moisture. To avoid appreciable errors it has been found necessary to avoid final weighings of oven-dried samples on excessively moist days.

The discovery that within certain limits the moisture of the soil follows the laws of osmosis, or more precisely speaking, the laws of dilute solutions with respect to its freezing point, has naturally led to the idea that the soil solution might also be considered as having a definite vapor pressure at a definite osmotic concentration. If this were true, then a soil placed in a moist atmosphere should give off or absorb vapor, according to whether its original solution represented a lower or higher osmotic pressure than that represented by the atmosphere of vapor in which it was placed. Furthermore, if this vapor pressure manifested itself properly and in accordance with the laws of solutions, then, through vapor transfers, one soil or a hundred soils simultaneously might be brought into vapor-pressure equilibrium, and thereby into osmotic equilibrium, with a solution whose osmotic pressure is readily determined; and the moisture contents corresponding to such osmotic pressure might then be readily measured for one or all of the soils. This plan was conceived as a possible means of avoiding some of the difficulties of the freezing-point method of osmotic determinations, which are especially bothersome in treating coarse soils. That the theory is correct may hardly be questioned now, and full discussion of the available data will be given later. This subject has been mentioned here because of its possible bearing on the hygroscopic coefficient determinations. It is rather readily seen that, if the laws of solutions prevailed under all conditions of soil moisture, a soil exposed to completely saturated water vapor should go on absorbing moisture indefinitely, because the dilute solution of the soil would always stand for some osmotic pressure, while saturated water vapor would stand for none at all.

Whether this does not occur in the hygroscopicity tests because of the failure to create a completely saturated atmosphere, or because there is a sharp line between the behavior of water vapor in the soil and liquid water, is for the future to decide. That it probably has no practical bearing on the hygroscopic coefficient under the empiric conditions set for that test, is perhaps enough in itself. It will help to clarify the matter if it is remembered, first, that Bouyoucos (109) has shown that at about the moisture content at which wilting occurs, the water of the soil ceases to behave as a liquid and refuses to freeze; and secondly, that Briggs and Shantz (114) have shown that the hygroscopic coefficient falls considerably below the wilting coefficient, the former being usually about 0.7 of the magnitude of the latter.

Since the determination of the hygroscopic coefficient begins with air-dry soil, it does not deal with liquid water in the soil, but more probably with water molecules more or less separated, like individual vapor molecules.

The conditions under which the hygroscopic coefficient should be determined, as most recently worked out by Alway, Kline, and McDole (103), are briefly as follows:

1. The absorption box is of wood, 12 by 9 by 8 inches, the interior surfaces being paraffined to prevent absorption of water and warping. Larger boxes were found to be more difficult to keep saturated.

2. In the bottom of this box is placed a snug-fitting galvanized-iron tray, 3 to 4 inches high, to hold the water. The walls of the box are then lined with blotting paper, the edges of which project into the vessel of water. This insures rapid dissemination of vapor through the interior.

3. A wooden table is held by metal supports, 1 to 2 inches above the surface of the water in the tray. On this table are placed the two trays which hold the soil samples.

4. Metal trays are accepted as most satisfactory, because they absorb no moisture and hence do not retard absorption by the soil. These trays are of aluminum or copper, 7 inches long, 5 inches wide, and 0.75 inch deep.

5. The soil is carefully sifted over the bottom of the tray to a depth of 1 millimeter. This naturally precludes the use of coarser material. It was found that there was little or no change in soils from careful grinding which would barely permit the coarser particles to pass a 1-millimeter sieve. It was also found that oven drying at 105° to 110° C. did not appreciably affect the absorbing capacity of any of the soils tested. In any case, however, previous drying should be avoided when possible.

6. The exposure to vapor in the boxes is for 24 hours. At the end of this period the soil tray is removed from the box as quickly as possible and emptied into a stoppered weighing bottle, since exposure to the air beyond a few seconds would cause appreciable loss of moisture.

7. Undoubtedly the most important consideration in securing reliable results is a suitable room. This must be, in most cases, a cellar room not subject to daily fluctuations of temperature or heating from one side, or even to localized heating from bright light. These precautions are absolutely vital, if condensation is to be prevented. As a matter of theory, it is altogether probable that the need is to prevent even momentary complete saturation of the vapor in proximity to the soils, since this might give rise to the creation of liquid moisture in them, and entirely alter their condition.

8. A temperature of about 60° F. may be considered a standard. At a lower temperature there will be fewer water molecules reaching the soil, and, necessarily, a slower rate of absorption.

Under these circumstances fairly constant results may be expected in hygroscopic coefficient determinations. In the absence of any other results reference is again made to the comparisons made by Briggs and Shantz between hygroscopic and wilting coefficients. In 17 tests, with soils varying from 0.9 to 16.5 per cent wilting coefficient, they found the ratio of hygroscopic to wilting coefficients to be on the average 0.680, with a probable error, or variation, in any single determination of about 7.1 per cent of the wilting coefficient. It is to be noted that the hygroscopic is so much lower than the wilting coefficient that serious error would result from considering them as interchangeable, though this proposal has sometimes been made.

CALCULATION OF THE AVAILABLE MOISTURE.

As has been stated, when the current moisture of the soil has been measured, and the nonavailable has been measured in the laboratory by the direct method of wilting tests, or indirectly through the capillary moisture, moisture equivalent, or hygroscopic coefficient, it is then only necessary to subtract the wilting coefficient from the whole moisture to have a measure of the amount of water which, under the most favorable circumstances, will be available for growth. For example, if in sand and clay, respectively, the whole moistures are 10 and 20 per cent, and the wilting coefficients of these soils are respectively 2 and 15 per cent, then it is evident that in the sand there is 8 per cent available moisture, and in the clay 5 per cent, or $A = M - WC$. The use of the last figures is certainly far more expressive of the relative conditions in the two soils than would be the use of the whole moisture figures, although, on account of varying concentrations of salts, even this figure for the available moisture does not give a direct means of comparing the moisture conditions of radically different soils.

Of course, if the measure of available moisture is to be used most fully as an index to supply, the percentage should be transposed finally into cubic centimeters per cubic meter, or any other measure of soil volume.

This is very readily done if the apparent density has been determined, as in the large capillary cans described, where the apparent density is obtained by dividing the dry-soil weight, in grams, by the volume in cubic centimeters, which is approximately 1,030 cubic centimeters (usually less after centrifuging).

Carrying the volume idea still farther, in studying any plant or group of plants it is obviously desirable to know how much soil surface can be drawn upon. Thus a yellow pine on a dry site may actually have a much greater supply of moisture than a crowded spruce on a moist site. Consideration of this point of view will lead to the conclusion that soil moisture figures, as ordinarily given in percentages of the dry-soil weight, have almost no significance ecologically. Both area and depth of soil which contribute to a given plant must be known.

AVAILABILITY OF THE MOISTURE.

As already stated, it is intended to confine this term "availability" to the simple relation between the whole moisture and the available moisture. The term can not be an exact expression of the rate at which the plant will be able to obtain water, since such rate depends on conditions within the plant as well as those without; or, in brief, on the need of the plant for water. It should, however, have greater value than a bare measure of whole moisture, or even of available moisture in percentage of dry soil weight as an expression of a condition of the soil. Its value is predicated on the assumption that, at the wilting point, a given plant is probably exerting a fairly definite osmotic pressure in its effort to obtain water, and that at this time the osmotic pressure of the soil water is also definite and the same as that in the plant. This is evidently not the case if the wilting coefficient is as low as the point at which both the water and solutes become adsorbed by the soil colloids, for at this point the osmotic pressure becomes infinitely large. For this reason the proposed measure of availability may have only limited usefulness, but should at least serve as a stepping stone to the next and more definite proposal.

If, for example, it is assumed that when a plant wilts it is exerting an osmotic pressure, P, of 100 atmospheres, then supposedly at the same time (that is, in the condition expressed by the wilting coefficient) the soil is exerting an opposing force, P′, also represented by 100 atmospheres. If, then, an amount of water equal to the wilting coefficient is added to the soil, the soil solution, roughly speaking, has been diluted to one-half its previous strength, and there is a differential in favor of the plant of 50 atmospheres. Since the starting point was 100 atmospheres, this situation, or the availability for this particular plant and soil, may be expressed as 50/100 or 0.50. Similarly, when the moisture content is three times the wilting coefficient, $P'=33$ atmospheres, the differential is 67 atmospheres, and availability is 0.67. It is seen that this is readily expressed by

$$\text{Av.}=\frac{M-WC}{M}$$

giving availability numerical values somewhat proportionate to the osmotic pressures in favor of the plant.

THE COEFFICIENT OF AVAILABILITY.

As already suggested, the ability of the plant to supply itself with water would seem to be measurable in terms of the differential between the osmotic pressure within the plant and the antiosmotic pressure exhibited by the soil moisture, with an allowance for the distance through which this force must operate. This same basis was used in the preceding section as a rough means of showing changes in the soil condition, but without any allowance for changes in the absorbing power of the plant which occur with its loss or gain of water, or without considering the factor of height and distance as it may affect tall trees.

In attempting thus to express the availability of water to the plant, in precise terms or osmotic pressures, currently for any condition that may be encountered in the soil or plant, it is necessary to determine the osmotic pressure of the soil or plant quickly and accurately.

The osmotic pressure of an aqueous solution is determined by the increase in its boiling point over that of pure water; by the depression of its freezing point; by the decrease in the vapor pressure over the solution; and, possibly, by the increase in the latent heat of vaporization. It is only recently that investigations of the last have been made, so that there is no known formula which would make this process available.

Within the limits of so-called dilute solutions a rise of 1° C. in the boiling point represents an osmotic pressure of about 57 atmospheres; a depression of 1° C. in the freezing point indicates $P=12.05$ atmospheres, and a depression of 1 per cent in the saturated vapor pressure over the solution, the temperature being the same, indicates about 12 atmospheres pressure. These approximate figures permit us to judge of the practical utility and accuracy of different methods.

It may also be useful at this point to refer to the fact that in pure solutions, such as may be used in the vapor-transfer method or in plasmolytic tests on tissues, the osmotic pressure is very readily determined by the concentration of the solution, in terms of the molecular weight of the solute, provided the solute is chemically pure and anhydrous. According to Nernst (134) the "molecular lowering of the freezing point" for water is 18.4° C.,[12] or 1.84° C. when 1 gram molecule of the substance is dissolved in a liter of water. A 1-molecule solution, therefore, stands for 22.12 atmospheres osmotic pressure.

From these data it would seem that the boiling-point method would insure the greatest precision in osmotic pressure determinations, were it not for the effect on the boiling point of the character of the vessel itself, of gases in the liquid, and of solid particles which form nuclei for steam bubbles. It is also self-evident that the boiling-point method is not applicable to soils, and hardly more applicable to plants unless the sap has been separated from the pulp, which, under certain circumstances, as in the treatment of conifers, may be impossible of attainment.

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[12] More recent investigations reported by Jones *128* show that the molecular lowering may be twice this amount in the case of salts which are dissociated by water into two ions. Freezing-point determinations should quickly decide this, in case of doubt.

The freezing-point method comes next in order, and has been considerably used; though, at this stage, it is well to mention that the foliage of coniferous trees frequently becomes so dry that a definite freezing point can not be determined, probably because of the lack of conductivity in the mass, which is such that each particle of the pulp may freeze without affecting the rest of the mass quickly.

The vapor-pressure method does not look so promising, because of the technical difficulties in the way of any precise determination of vapor pressure. However, the complicated apparatus necessary for the direct determination of a vapor pressure may be done away with if instead the determination of vapor pressure is made in a vessel by means of a solution which is in equilibrium with that vapor. This method especially commends itself in the treatment of soils because of the possibility of preparing them and retaining them during treatment in a state of compactness and granulation approaching the natural. It does not seem so applicable to plant tissues because of the danger of fermentation and enzymic action during the treatment.

The determination of osmotic pressures in plant cells by plasmolysis, while evidently useful for the examination of restricted areas, such as the epidermis, and possibly useful for any tissues which are exceedingly dry, does not recommend itself for general purposes because of the large amount of manipulation necessary and the experimentation required to find the balancing solution. This method, of course, necessitates the observation of individual cells under the microscope, when placed in media of various osmotic concentrations.

Osmotic Pressure of Plant Tissues.

Dixon and Atkins (119), in 1913, were apparently the first to use the then developing theoretical knowledge of the behavior of solutions as a means toward looking into the internal conditions of plants. In the citation given they deal at length with the method of extracting sap from plant tissues for the purpose of freezing-point determinations.

Hibbard and Harrington (126), in 1916, and Harris, Lawrence, and Gortner (123), in the same year, followed this work with further studies of the method of determining the freezing point of cell saps, and also applied this knowledge to the study of plants under various habitat conditions. The latter were probably the first to point out that the osmotic pressure of the cell sap varied rather directly with the dryness of the habitat. They also showed that trees and shrubs possess higher pressures than the lower and shorter lived forms of vegetation, which furnishes the basis for considering height as a factor affecting the osmotic pressure in the leaves.

McCool and Millar (131), 1917, experimented with unpressed plant tissues and obtained practically the same results as when the extracted saps were used. This was a distinct step forward in simplifying the process, and therefore no attempt is made to describe the method of sap extraction. McCool and Millar found it only necessary to macerate slightly the material with a stiff wire, in the freezing tube. These investigators also brought out much new information on the changes in osmotic pressure in the leaves with atmospheric changes, and the close correlation between root pressures and conditions of the soil moisture, the former being little influenced by atmospheric conditions.

Bates (105), in 1917, seeking an explanation of the great difference in the transpiring capacity of different species of tree seedlings, and not being equipped with freezing-point apparatus, obtained the sap density of the aerial portions of whole seedlings by grinding them in a food grinder, extracting the water-soluble substances, filtering the liquid, and then drying the water-soluble solids and the washed pulp separately. The weight of these two, when deducted from the original weight of the plant, gives the weight of the original solvents, and the "sap density" is expressed by the ratio between solutes and solvent. These first results were found to have a close relation to the transpiration rates that had been observed, and it was therefore concluded that sap density might very largely serve as an automatic restriction on transpiration.

Although realizing that an expression of osmotic pressures would give a more reliable basis for comparing the species, this was not undertaken for some time, since it was desired to establish first the importance of the sap density as a measure of the condition of the plant and its response to various atmospheric conditions. This work has been pursued to some extent.[13] It is only desired here to state that, within the limits of experimental error, the osmotic pressures shown by a number of the conifers appear to be the same when the sap densities by the above method are the same. Considering all of the species, the following correlation between the two measures is given tentatively:

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[13] "Forest Types of the Central Rocky Mountains," by C. G. Bates. Unpublished report.

Sap density.	Osmotic pressure.
Per cent.	*Atmosphere.*
5	4.5
10	10.0
15	15.7
20	22.4

For rough approximations, the osmotic pressure in atmospheres may be considered equal to the sap-density percentage for plants of this class. It is probable that further data will bring out specific differences worthy of consideration. It is, therefore, believed that where freezing-point determinations are impracticable because of lack of apparatus, or of freezing mixtures; or when, as frequently happens with the foliage of conifers, the material is so dry that even with grinding it lacks free moisture, so that a distinct end point can not be secured, the sap-density method may be of very great assistance.

After considerable experimentation with a number of methods giving essentially the same results, the following simple practice has been developed, which is designed primarily to eliminate the need for evaporating the large volume of water used in extracting the solutes; it also greatly reduces the opportunity for loss of material during the operation.

1. The plant material, usually consisting of the more exposed and consequently the drier portion of the needles, is secured by carrying into the field the desired number of wide-mouthed liter flasks, a funnel, and a pair of shears. The plant, or branch of a tree, is held over the funnel, and the leaves are snipped off in sections not over one-half inch long, the outer one-half to two-thirds of all needles being taken. When 10 to 15 grams of material has been secured, the flask is stoppered. As soon as a collection has been completed, the flasks are taken in and weighed with their contents, the flask weights having previously been recorded. Confusion may be avoided by making all weighing with the stoppers removed.

2. The flasks are now placed in the drying oven for a period of not less than 12 hours. It will usually be found convenient to have the specimens ready for extraction early in the morning. At this stage the weight of flask and dry contents is secured, and by the difference between this and the earlier weight, the original water content is obtained directly.

3. Each flask now has added to it distilled water to the extent of five times the weight of the green plant material and is then again placed in the oven for an hour, the temperature attained in this time

being practically that of boiling water, which will greatly facilitate the diffusion of the solutes. While this warming is being accomplished, a filter may be prepared, corresponding to each flask. The filter papers are dried and weighed before using, and their weights credited to the samples with which they will be used. At the end of the hour the liquid contents of each flask are poured into their appropriate filters.

4. Water is again added to each flask, in the same amount as before, and the process repeated. After the third extraction, with possibly a little cold rinsing of the pulp, filter, etc., the filter, with whatever solids it has accumulated, is placed in the flask, and this is returned to the oven for its final drying. After this, making allowance for the filter-paper weight that has been added, the loss of solutes is readily computed. It should also be realized that this loss will include a small proportion of water which was hygroscopically held by the solutes in the previous drying. Such loss, however, will possibly compensate for solutes not removed. While the three extractions, theoretically, should remove more than 99.9 per cent of the solids, it is probable that they fall appreciably short of this.

Since it is believed that investigations along this line will develop increasing importance in forest ecology, it seems advisable to make available a table of osmotic pressures for freezing-point depressions to 5.999° C., as worked out by J. A. Harris and published in the American Journal of Botany, 2:418–419, 1915. This is an extension of the work begun by Harris and Gortner in 1914. The table will be found in the appendix.

Of almost equal ecological importance with the increase in osmotic pressure and absorbing capacity which accompanies greater concentration of the cell sap, is, perhaps, the very great decrease in the probable rate of evaporation from the leaves. It is especially desired to call attention to this, since the earlier announcements of the findings of physical chemistry have led many biologists to believe that a considerable change in the osmotic pressure of the plant solution could have little effect on evaporation. Thus Livingston (130), in 1911, argued that the greatest concentration of the cell sap would only create a depression of 10 per cent in the vapor pressure over the solution, and consequently could have no important effect on the evaporation rate.

As early as 1915, Bates (105) had observed in the artificial drying of pine cones, for which a calorimetric kiln was used, a very great increase in the amount of heat consumed as the drying advanced. In certain instances this was nearly three times as great, per unit of water evaporated, in the final stages as when beginning with very green cones. When, therefore, he found, in 1917, a great decrease in the transpiration rate of those species of conifers which showed the highest concentration of the cell sap, he was led to investigate this matter further. Finding nowhere any reference to experiments on the latent heat of vaporization of solutions, and believing that the conception of the fixed nature of that quantity for water was based upon the fact that the condensation of steam had always been employed to determine it, he has been led to perform a number of experiments with solutions and with distilled water.

The most important and convincing of these shows that at the respective boiling points of water, and various solutions up to the point of saturation (for sodium chloride), the latent heat of vaporization, determined directly by means of an electric heating element, is practically a constant, though perhaps varying inversely as the absolute boiling point. Thus a saturated salt solution whose boiling point is 7° above that of water and whose osmotic pressure is theoretically about 400 atmospheres, requires only 4 per cent less heat, per unit of water evaporated, than does pure water. This, however, does not solve the problem, as will be seen from the fact that when placed over a steam bath the saturated salt solution evaporates at a rate of less than 5 per cent of that for pure water. There is in the problem, therefore, very evidently some factor besides vapor pressures and latent heats of vaporization when an external supply of heat is concerned. It appears to be a matter of conductivity and possibly also of convection. Further investigation of the problem is urgently needed.

Method of determining freezing points.—Since, as has been stated, the treatment of the leaves of forest trees, especially conifers, is likely to present some complications because of the extreme dryness which they sometimes show, it is believed the whole-tissue method of McCool and Millar (131) is likely to be ineffective. Hibbard and Harrington (126) are therefore quoted here on the process used by them and involving grinding of the frozen tissues. From this basis any investigator will certainly be able to devise modifications to suit his special conditions.

> The apparatus used in our tests was the Beckmann outfit ordinarily used for such work and described in books on physical chemistry, consisting of a Beckmann thermometer, freezing tube, outer jacket, and a battery jar containing the freezing mixture. The freezing point of distilled water was taken as zero, and the lowering of the freezing point of the pulp was obtained by subtraction. When determining the freezing point of distilled water an electric stirring device was used consisting of battery, metronome, magnet, and platinum stirrer, but this was not employed in determinations made upon pulps. The pulp was allowed to undercool about 1°, after which the beginning of solidification was brought about by rotating the thermometer backward and forward a few times in the pulp. When the undercooled mass of pulp was thus disturbed the temperature began to rise almost immediately and soon came to rest, after which the thermometer was tapped several times and the

final reading then taken. This reading was considered as the freezing point of the pulp tested. Correction for undercooling has not been applied, since the undercooling was always the same. Since, as has been especially emphasized by Shive,[14] the external air temperature exercises a marked influence on the apparent depressions of the freezing point obtained by means of the Beckmann apparatus, the freezing of the pulp or expressed juice must always be carried out with aproximately the same temperature of the surrounding air as prevailed during the determination of the freezing point of distilled water used for comparison with that of pulp or juice. The simplest way to avoid possible sources of error in this connection is to make a freezing-point determination on distilled water for each external air temperature at which pulps or juices are tested. Then the lowering for any test is considered as the difference between its freezing point and that obtained on distilled water with the same room temperature.

The property of the solution upon which its maximum possible osmotic pressure depends is approximately measured by its freezing point lowering, and this property may be expressed in terms of pressure. Thus, according to the formula of Lewis,[15] $\Pi=12.06\Delta-0.021\Delta^2$, where Π is the maximum osmotic pressure, in atmospheres, at the freezing point of the solutions, and Δ is the lowering of the freezing point in centigrade degrees, below that of distilled water. With the aid of this formula Harris and Gortner[16] have prepared a table of the values of Π for the range, $\Delta=0.001°$ C. to $\Delta=5.999°$ C. This table has been employed in our deductions.

At the beginning of the work the material to be used was first ground and then frozen, but it was difficult to prevent some loss of sap in this way, and difficulty was also encountered in getting a perfect mixture of the material after thawing, since much of the sap had left the cells on grinding and had settled to the bottom of the mass. Consequently, it was found better first to freeze the material and to grind it afterwards. In the earlier tests this preliminary freezing was carried out in large test tubes immersed in a mixture of salt and ice at a temperature of from —12° to —17° C. Sometimes during cold weather the material was placed out of doors overnight for the preliminary freezing. In the remainder of the work it was frozen by carbon dioxide and ether. Carbon dioxide was obtained in the solid state by allowing the compressed gas to escape from the supply cylinder into a small cloth bag. The material to be frozen was placed in a beaker and completely covered with solid carbon dioxide. A small amount of ether was then added, until complete freezing had taken place. A temperature of approximately —120° C. may be obtained in this way.

The tissue is reduced to a finely divided condition by grating or grinding in a food grinder. The ground material must be quickly and thoroughly mixed before sampling, since as would be expected, and as has indeed been found by other investigators, not all parts of a given organ give the same concentration of sap. Unless great care is taken in mixing, two or more samples of the same pulp do not have the same osmotic concentration.

Samples are placed in the freezing tubes and allowed to thaw completely before the determination of the freezing point is made. When the tissue is ground and pressed before the preliminary freezing many serious changes may take place; enzymes may be liberated, many new chemical reactions may be brought about, and the solutions may change in various physical ways. After thawing, the material should be stirred with a glass or suitable wooden rod to expel all air bubbles. Thawing may be completed within 15 or 20 minutes at most, and the possibility of chemical change is thus very greatly reduced. When thawing is complete, the thermometer is inserted, the tube is placed in the freezing mixture, and the material allowed to reach a temperature about 1° below its freezing point. Solidification is then brought about, as has been stated, by turning the thermometer backward and forward a few times to create a slight disturbance in the pulp. It has been found in practice that much more satisfactory results are obtained if the material is thus allowed to undercool about 1° than when solidification is brought about with less undercooling. In the latter case the mercury rises to the freezing point much more slowly and the determination of this point is consequently more difficult.

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[14] Shive, J. W., The freezing-points of Tottingham's nutrient solutions. Plant World 17; 345–353, 1914.

[15] Lewis, G. N., The osmotic pressure of concentrated solutions and the laws of the perfect solution. Jour, Amer. Chem. Soc. 30: 668–683, 1908.

[16] Harris, J. A. and R. A. Gortner. Notes on the calculation of the osmotic pressures of expressed vegetable saps from the depression of the freezing point, with a table for the values of Π for $\Delta=0.001°$ C. to $\Delta=2.999°$ C. Am. Jour. Bot. 1: 75–78, 1914.

Harris, J. A., An extension to 5.999° C. of tables to determine the osmotic pressures of expressed vegetable saps from the depression of the freezing point. Amer. Jour. Bot. 2: 418–419, 1915.

Osmotic pressure in soils.

Although it is possible to remove the soil solution from the soil and to determine its osmotic pressure by the freezing-point method, this will fall far short of the desired end, which is to determine how the water behaves in the presence of the capillary forces and adsorption tendencies of the soil particles and colloids. As has been suggested in the introductory paragraphs to this chapter, these influences may run parallel with the influences of dissolved salts in the soil water.

The freezing-point determinations for moist soils are so similar in method to those for plant pulps that it seems unnecessary to describe them here in detail. The reader is especially referred to the description given by Bouyoucos (107). It would seem that the fundamental consideration in testing a given soil at various moisture contents is to have samples very evenly wetted. This is accomplished by placing the sample in a moisture-tight jar and, after thorough shaking, allowing it to stand one or more days, so that the moisture is evenly distributed and has ample opportunity to be adsorbed. While it is possible to use measured amounts of water in wetting the soil, it is probably safer procedure to take moisture samples at the same time that samples are taken from the jar for freezing tests.

Vapor transfer in soils.—The vapor transfer method is the only other method of osmotic determination which appears feasible for soils, and where time is not an important element, it is believed to be preferable to the freezing-point method because of the possibility of treating soils in their natural states. It should be understood, however, that the value of the method is as yet theoretical rather than proven.

The work of Alway (103) and Hilgard (125) on the hygroscopic coefficient of soils has already been mentioned, with the suggestion that since the moisture boxes used could not completely prevent the vapor from escaping, their results are not indicative of those to be expected when vapor pressures are maintained in true equilibrium with solutions of reasonable osmotic pressure. As has been stated, a solution showing 12 atmospheres pressure will be in equilibrium with vapor 99 per cent saturated, and even this degree of saturation, it is believed, would be extremely difficult to maintain except in a fully sealed vessel.

On the other hand, Patten and Gallagher (136) have carried out experiments, both on absorption of vapor and evaporation from soils, in "desiccators" which are assumed to be similar to the bell jars mentioned hereafter, and which, while usually not strictly vapor proof, approach much nearer to the ideal condition. Patten and Gallagher, both in their review of earlier work and in their own experiments, have established a number of salient points which assist in the proper conception of the relation between vapor (or, to a certain extent, gas) molecules and solid particles, such as those of the soil. Schübler[17] and Davy[17] are quoted as having shown that, in general, the finer the texture of the soil and the greater its content of humus, the higher is the absorption capacity of soil for water vapor. These results, while actually referring to the initial rate of absorption, are fairly indicative of the forces with which various soils attract water vapor. Von Dobeneck[17] obtained similar results, though concluding that large grains absorbed more vapor per unit of surface than small ones. Each soil particle reacts upon vapor molecules independently, and each has a specific relation to different kinds of gases. Several investigators have decided that the absorption of vapor decreases with an increase in temperature, even though the absolute vapor pressure increases proportionately. Patten and Gallagher have carefully proven this. Hilgard's contrary finding may be explained on the basis that he was dealing almost wholly with rate of absorption, and higher absolute vapor pressure should more quickly bring about equilibrium. Mason and Richards[17] found that cotton fiber containing water resembles a solution in exhibiting a definite partial vapor pressure.

Patten and Gallegher's most important results have to do with the rates of absorption of vapor, and with evaporation, in the presence of various vapor pressures controlled by sulphuric acid solutions and vessels of water, within desiccators. The rate of absorption by dry soils increases, and the rate of evaporation from wet soils decreases quite regularly as the partial vapor pressure in the desiccator is increased. It is, however, evident in all of the results that as the vapor pressure approaches saturation the amount of absorption increases in greater proportion than does the vapor pressure. A number of the graphs are strongly suggestive of the idea that, if complete vapor saturation were attained, the absorption by the soils might be unlimited.

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[17] For complete citations see Bureau of Soils, Department of Agriculture, Bulletin 51.

With partial vapor pressures over acid solutions, practical equilibrium was reached in all soils at the same ultimate moisture content, whether the soil was started in a moist or dry condition. Thus Sea Island cotton soil, which was the finest used, dried out at a vapor pressure of 17.90 millimeters (76 per cent of saturation) in 97 days from 55 per cent to 6.08 per cent moisture, and the same soil absorbed in the same period 5.6 per cent, starting from a dry condition. In the presence of a vessel of water the drying out was always very slow, and the fact that any drying whatever occurred is believed to be sufficient evidence that the atmospheres in the desiccator were not saturated, owing to the presence of the dry soils in the same atmospheres.

Finally, the energy effects of absorption must not be overlooked. Patten and Gallegher cite a number of investigations which show that the heat released when vapor is absorbed by a soil is in excess of the latent heat which is released when vapor condenses. This fact indicates that water held in the soil, like water held in a solution, is brought to a greater density than that in which only water molecules are attracting each other. This density can only be obtained through the release of additional energy.

Examined kinetically, then, the whole situation is fairly simple. Molecules of a gas or vapor repel one another, and this repulsion increases with the temperature and energy of each molecule. When a certain density is obtained in a volume of vapor, the so-called saturation density, the molecules may either return to the liquid from which they emanated or be compelled to unite with other molecules, starting condensation in the molecular sense. In the case of atmospheric vapor, solid particles, such as dust particles, may start condensation through their attraction for vapor molecules, which latter would otherwise repel one another too strongly to be brought together.

The same phenomena occur in the soil. A soil particle of given size, mass, and gravitational power can attract to itself a certain number of vapor molecules, this number depending upon the space available and the distance at which the vapor-molecules begin to repel one another, or the temperature and energy of these molecules. A vapor molecule which has been trapped, and has given up some of its energy in this process of "individual condensation," is relatively inert, but not so inert as the soil particle, and is still capable of repelling other molecules to some extent. The ultimate number of molecules that can be held in a given soil, therefore, must depend (1) primarily on the energy of the free molecules as governed by temperature; (2) on the area or surface of soil particles exposed.

such that vapor molecules remaining on said surfaces do not crowd one another; (3) on the size of the particles, the smaller particles having less gravitational power; and (4) on the extent to which the substances in the soil act as solids or crystals with only exterior surfaces available, as spongy masses capable of absorption, or as individual molecules each of which may attract and retain under partial control a sufficient number of molecules, so that in the aggregate the conditions are those of a liquid.

The factors that affect the rate of absorption are far less important, but might be briefly mentioned, as follows: (1) The size of soil spaces as affecting free passage of vapor molecules; (2) the number of chances for a given molecule in motion through a given space to encounter an attractive force too strong for it (this has to do with the number of particles per unit of volume, as well as size of air spaces); (3) the density of the soil particles; (4) the density of the vapor molecules as affected by temperature and whole pressure; (5) the conductivity of the soil, governing the rate at which the heat of condensation can be eliminated from the soil mass.

This examination of established facts and theory regarding vapor condensation in soils leads to the recent efforts by Bates (105) to show that the moisture of soils does exhibit a definite partial vapor pressure corresponding to that of a solution, and that the vapor transfer method has many latent possibilities. It should be stated that these investigations are not yet complete or convincing, but in some respects they have gone farther than any others and are worth mentioning at least as suggestions for further effort.

The vapor-transfer method of Bates.—In its simplest form the vapor transfer method is similar to the plasmolytic method in attempting to find a point of osmotic equilibrium between the soil moisture and solutions of known concentration. In this case equilibrium must be shown by the cessation of transfer of water, through vapor, from the soil to the solution, or the reverse. It would be possible to take a number of samples of a given soil at a known-moisture content and place them in relatively small chambers, each with a solution of different concentration from the others, and in the case in which there was no transfer from the soil to the solution or vice versa equilibrium would exist and the osmotic pressure of the soil water could be directly calculated from the known concentration of the solution.

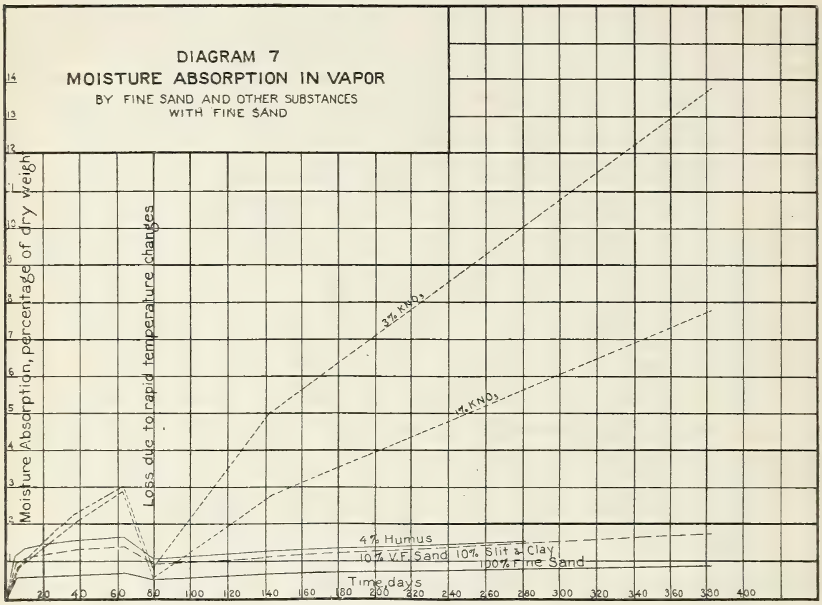
In practice, however, it is far more feasible to place the soil sample of known moisture content in the vapor of a solution of approximately the same osmotic pressure, let the two come into equilibrium through vapor transfers, then compute the moisture content of the soil, the osmotic pressure of the solution, and the approximate original osmotic pressure of the soil on the assumption that the osmotic pressure varies inversely as the moisture content. The latter is probably true only within rather narrow limits.

Further, since obtaining an equilibrium by vapor transfer is a slow process, it is desirable to be able to treat a large number of soil samples simultaneously. For this purpose a large-size bell jar, resting upon plate glass, may be employed. A pressure cooker, the cover joint being properly sealed, has also been found very useful. There may be one or more vessels of the solution, and as many vessels of soil as are desired, within the chamber. Using 2¼-inch soil cans for soil containers and similar beakers for solutions, about 60 soil samples may be treated at once under a 14 by 12 inch bell jar. However, a great deal of evidence shows the desirability of a relatively large vessel for the control solutions, and a decrease in the number of soil samples.

It should be remembered that this treatment will only give the osmotic pressure for each soil at one particular moisture content, which will depend upon the total amount of water in all of the samples, as well as upon the concentration of the control solution, at the initiation of the test. To obtain a range of values for any soil, separate tests must be made under varying conditions.

The fundamental provision in such a test is that the vapor chamber should have a constant temperature and be evenly heated on all sides. To accomplish this most simply a deep excavation in the ground is desirable. The very gradual seasonal change of temperature in such a situation will not work any harm, since the vapor pressure within the chamber will adjust itself to such a change without necessitating any condensation. In the lack of this, a dark cellar may be chosen.

In proof of the theory that a soil solution would continue to absorb water indefinitely in the presence of saturated water vapor, and that, therefore, the hygroscopic coefficient as now known is a purely empiric quantity, a test has been conducted for slightly more than a year with clean sand and various modifications thereof which represent the different elements encountered in various types of soil. The sands and modified sands were all placed in the vapor chamber in an oven-dry state, together with a bottle of distilled water with linen wicks having about 10 square inches of evaporating surface. The successive weighings of samples and bottle indicate that some vapor is constantly escaping from the chamber, so that the vapor therein is never absolutely saturated. Early in the test it was found impossible to heat the chamber as evenly as desired in the cellar in which it was placed, so that it was removed for a time to an electrically heated incubator. Here the fluctuations, though small, were rapid and a slight overheating at one time caused a very severe loss from all samples, the chamber being unable to hold the vapor under high pressure. The effect of this is seen in diagram 7, where some of the typical results are illustrated. In Table 5 is shown only the absorption for four periods, eliminating this period of general loss. Except this period, the exposure in the cellar has been at temperatures between 0° and 10° C., which, it will be noted, are lower than have previously been employed.



For several of the soil types duplicates were run. The results, however, are so nearly identical in each pair that only the averages need be given.

TABLE 5.—*Absorption of water vapor by Nebraska fine sand, and modifications thereof.*

[Basis 100 grams dry matter in 2¼-inch aluminum can.]

Number of samples.	Description of sample.	Absorption at end of—			
		5 days.	10 days.	63 days.	382 days.
		Per cent.	*Per cent.*	*Per cent.*	*Per cent.*
2	100 per cent fine sand, unwashed	0.56	0.58	0.68	0.80
1	100 per cent fine sand unwashed half-size [1]	.68	.68	.72	1.08
2	100 per cent fine sand, washed [2]	.57	.62	.69	.79
1	90 per cent fine sand, 10 per cent very fine sand	.51	.59	.64	.89
2	90 per cent fine sand, 10 per cent silt and clay	.97	1.10	1.33	1.59
2	80 per cent fine, 10 per cent very fine, 10 per cent silt and clay	.93	1.07	1.37	1.72
2	90 per cent fine sand, 10 per cent fine limestone soil	.72	.85	.96	1.27
1	90 per cent fine sand, 10 per cent calcium carbonate	.71	.89	1.55	2.05
1	99 per cent fine washed sand, 1 per cent KNO_3 [3]	.74	.98	2.88	7.75
1	98 per cent fine washed sand, 2 per cent KNO_3	.75	1.07	3.20	11.69
1	97 per cent fine washed sand, 3 per cent KNO_3	.73	1.03	3.01	13.77
1	98 per cent fine sand, 2 per cent ground decayed wood	.87	.99	1.13	1.61
1	96 per cent fine sand, 4 per cent ground decayed wood	1.15	1.33	1.64	1.68

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[1] To indicate effect of volume and depth on *rate* of absorption.
[2] Washed with 5 volumes of distilled water.
[3] Potassium nitrate applied in solution, and water evaporated before starting the test.

It should be borne in mind that the ideal temperature conditions were not attained in this test, and, as has been stated, that at no time has complete saturation of the vapor existed, except possibly for short periods during cooling. This ideal has, however, probably been approached more closely than in any previous test, and the long period employed gives us a new insight into the phenomena of absorption.

The following comments on Table 5 may assist in an understanding of these results. The comparative behavior of various soil combinations will not be discussed, as these merely substantiate the observations of others.

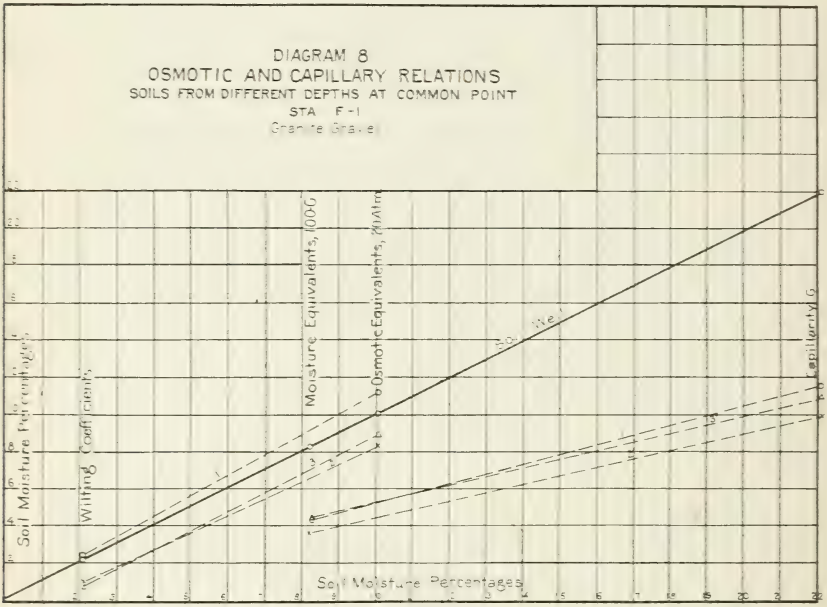
1. The amount absorbed by the unwashed fine sand in 382 days is only one-third more than the absorption in 5 days. It is, however, evident that even at the end of the longer period the unwashed sand was not in an atmosphere of saturated vapor, but rather in one whose pressure was quite as much controlled by the presence of soils still absorbing vapor, and particularly by the sample containing the largest amount of potassium nitrate. Assuming that all the moisture absorbed by the last entered into the salt solution, the latter would be a 22 per cent solution and would stand for an osmotic pressure of more than 45 atmospheres. It is therefore not surprising to find that a soil which contains not over 20 parts per million of soluble matter should make little gain in this atmosphere.

2. On the other hand, the amount absorbed by the fine sand in 382 days is just about equal to the wilting coefficient for this sand, as nearly as can be estimated from a test on the original soil, which contained about equal proportions of material finer and coarser than the fine sand.

3. The continued and relatively large absorption, especially by the soils containing active salts, might be ascribed to the low temperatures under which the test was conducted. It is believed, however, that the evidence of a condition slowly approaching saturation vapor pressure, and never quite up to it, is convincing, and that this explains not only the present results but nearly all the phenomena that have been reported in a similar connection.

A number of other tests somewhat similar to the above were made during 1918, but for short periods only. Several attempts were made to compare the osmotic pressures of soil samples in their natural moisture conditions, by placing the fresh samples under a single bell jar without a control solution, to note whether the samples gained or lost moisture in the common atmosphere. While these gains or losses indicated the relative dryness of the several samples, the tests were not continued long enough to produce any results of value. It was found that a period of two or three weeks was inadaquate to bring about equilibrium between the many samples, whose average weight was about 100 grams. Especially was it noted that surface samples which were nearly air-dry when taken absorbed very little moisture in these short periods.

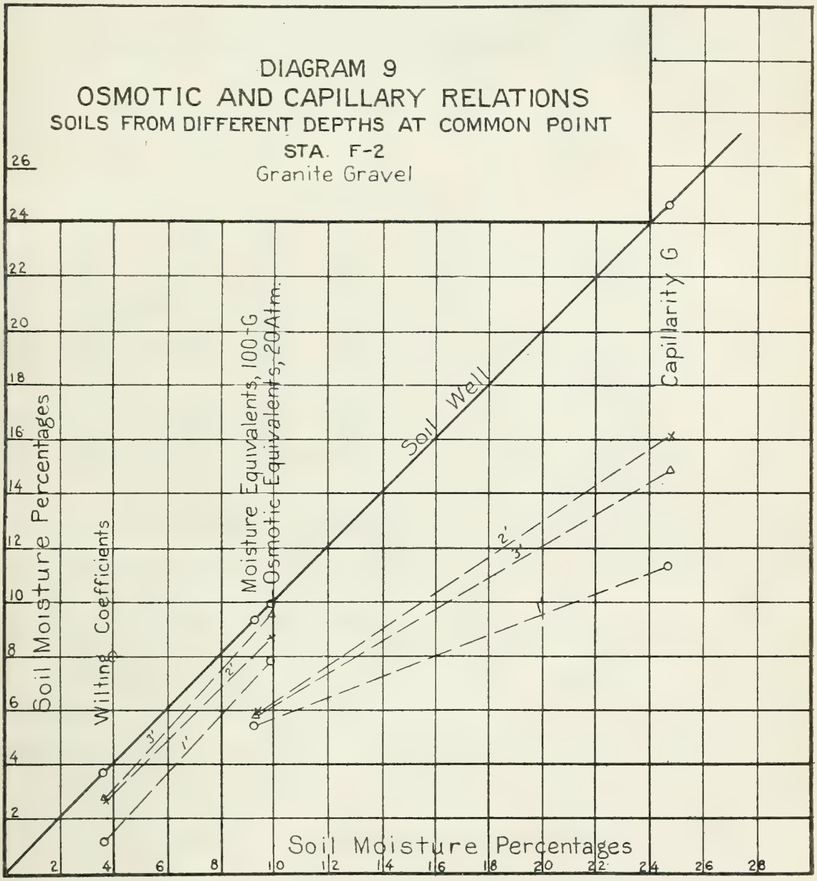
Finally, from November 28, 1918, to March 29, 1919, a test was made involving samples from nearly all of the regular soil-sampling points at the Fremont Experiment Station, as well as a miscellaneous lot exemplifying various peculiar characters. Two bell jars were employed, a small dish of sodium hydrate solution being placed in each. At the end of the four-month period these solutions had not absorbed vapor to quite the same extent in the two jars, and in neither case was the total absorption equal to the losses from all of the soils. However, for practical purposes the two containers were in equilibrium with each other, the osmotic pressures of the solutions being 21.5 and 20.2 atmospheres, respectively.



At the outset each sample of soil was given 10 per cent of moisture above its air-dry weight, so that the moisture was available in liquid form and the various soils were not radically unlike in their initial conditions. While it is not certain that the time allowed was sufficient to establish equilibrium, it is to be noted that the changes in moisture content varied from losses of about 3 per cent to gains of fractional percentages and, in one case, where there was much raw humus, a gain of 15 per cent.

The results, as shown in small part in Table 6 and diagrams 8, 9, and 10, are very elucidating. These diagrams are prepared somewhat in the manner suggested for interpreting the moisture data for soil wells and illustrated in diagram 3.

It will be noted on examining these diagrams, each of which represents the soils from various depths at a single point, that in each group of soils of common origin the lines drawn to connect the capillary moisture and moisture equivalent for each sample tend to converge toward the axis of the system of coordinates and give the suggestion that in any such group of samples these two measures will vary proportionately. On the contrary, there is a decided tendency toward parallelism in the lines connecting, for each soil, the wilting coefficient and the moisture content at the point of osmotic equilibrium established approximately by this particular test. If, for example, the last-mentioned moisture contents, which may be termed the "osmotic equivalents," be taken to correspond in every case to 20 atmospheres osmotic pressure, and if these be represented



by M′, and the excess over wilting coefficient by K, then in these diagrams the condition is represented by

$$M' = WC + K$$

rather than

$$M' = WC \times K,$$

since it is readily seen that the osmotic equivalents are not proportionate to the coefficients.

TABLE 6.—*Osmotic equivalent of soils, in presence of solution at 20 atmospheres, after four months exposure and other related properties.*

Station.	Depth.	Capillary moisture.	Moisture equivalent, 100-G.	Wilting coefficient.	Osmotic equivalent.	Excess over wilting coefficient.	Change in moisture during transfer.
	Feet.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Grams.*
F-1	1	11.64	4.29	2.31	11.19	8.88	+0.01
	2	10.00	3.60	.93	8. 7	7.34	−2.39
	3	10.96	4.34	.76	8.92	8.16	−2.35
	Well sand	22.08	8.25	2.13	[1] 10.06	7.93	[1] −0.72
	Av. of 3					8.13	−1.58
F-2	1	11.34	5.41	1.16	7.84	6.68	−2.62
	2	16.08	5.91	2.63	8.69	6.06	−2.20
	3	14.84	5.86	2.67	9.58	6.91	−1.67
	Well sand	24.70	9.29	3.67	[1] 9.87	6.20	[1] −1.24
	Av. of 3					6.55	−2.16
F-11	1	23.53	13.45	4.72	11.06	6.34	−1.90
	2	24.00	16.25	3.65	10.72	7.07	−1.80
	3	18.86	11.62	2.99	10.24	7.25	−2.11
	Well sand	21.61	6.67	[2] .76	9.90	9.14	−1.29
	Av. of 3					6.89	−1.94

[1] Average of 4 samples taken from each well, representing the surface and depths of 1, 2, and 3 feet, so that mean value should be equivalent to that of soil as placed in the well.

[2] Approximate. Test made on coarse sandy soil from depth of 4 feet, most nearly approaching the quality of sand used in the well.

Table 6 shows that K varies as between different groups of samples from different sources, but that within a group of similar origin K is essentially a constant. Thus, it has an average value of 8.13 per cent for one group, 6.55 per cent for another, and 6.89 per cent for the third, and this value seems not to have any constant relation to the change which occurred in the samples during their period of exposure, so that it may be accepted as representing something near a final condition. In one sample representing a limestone soil, K is found to be 17.12−15.33 per cent, or 1.79 per cent. In another soil of lava origin, containing less of silt and clay, but a considerable amount of sodium bicarbonate, K is found to be 12.23−4.44 per cent, or 7.79 per cent.

These findings compel the following conclusions:

1. The wilting coefficient of a given soil is probably dependent both on the solutes present and upon the colloids capable of adsorbing both the solutes and the water, but more particularly upon the latter; since only very rarely will the solutes be so abundant as to create an excessively strong solution before the disappearance of the free water.

2. The osmotic equivalent of the soil is almost wholly dependent upon the solutes present, and among soils of one general type, in which the ingredients are conducive to the creation of solutes at a definite rate, and their free transfer from one point to another, a given osmotic equivalent represents a fairly constant amount of free water plus a variable amount of unfree water, depending on the quantity of clay, humus, etc., in each sample.

3. In such a group of related soils the wilting coefficients may have some fairly constant relation to the capillary moistures or moisture equivalents, because both measures are affected by the water-holding power of the colloids in large part; but a capillary measure of the condition of the soil water is not alone a safe criterion as to its osmotic condition or availability at points considerably above the wilting coefficient.

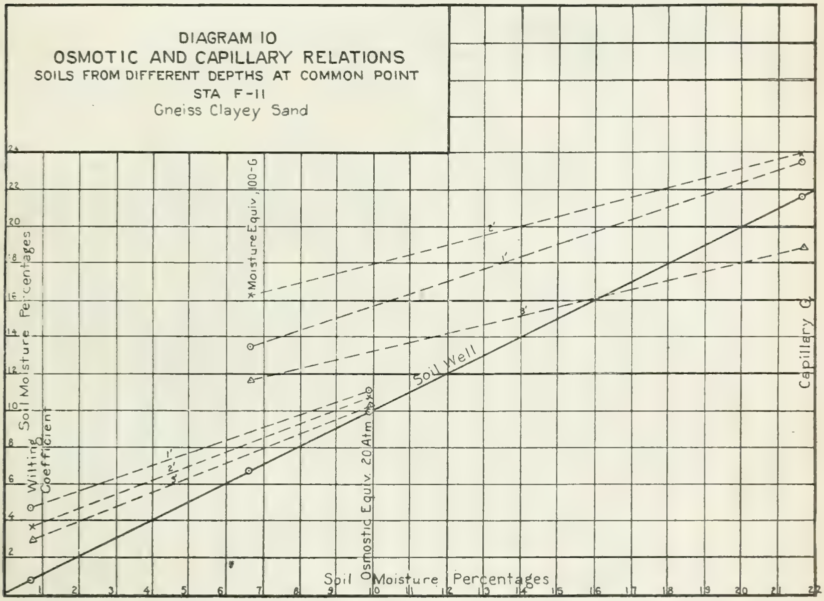


DIAGRAM 10
OSMOTIC AND CAPILLARY RELATIONS
SOILS FROM DIFFERENT DEPTHS AT COMMON POINT
STA F-11
Gneiss Clayey Sand

It is believed that these conclusions are essentially in accord with those of Bouyoucos (106) and Hoagland (127), as derived from their study of freezing points and osmotic pressures. Probably this conception of the factor affecting availability is of greatest value in explaining the poor growing conditions of undrained soils and the great preference of trees for those which are well drained. It is also of importance in indicating that soils of closely related origin may be compared, as to their current conditions, on the basis of the amount of free or available water in each. This proposition, it will be remembered, the writers were unable to accept with reference to soils of unrelated origins, which gave rise to the need for this whole investigation.

Computing the coefficient of availability.

In computing the coefficient of availability of the moisture at a given part of a tree or other plant, allowance must be made, as has been said, not only for the osmotic pressures at work in the plant and soil, but for the distance through which these must operate, and the effect of gravity on the balance between the two forces. As previously suggested, let

P =osmotic pressure in the plant,
P'=opposing pressure in the soil water,
$L=h$=height of plant in centimeters at point where P is determined,
G =weight of the column of water to be lifted, in atmospheres, or equal to $h\times 0.00097$ atmosphere.
AA, representing the coefficient of availability, is equal to

$$\frac{P-P'-G}{h}$$

It may then be assumed that the foliage of the tree, at a height of 30 meters above the ground, has been determined by its freezing-point depression to possess an osmotic pressure (P) of 25 atmospheres.

A more complicated case may also be considered. A soil, previously tested, is found to possess an osmotic pressure of 25 atmospheres at 4 per cent moisture content and of 5 atmospheres at 20 per cent moisture content, the former being appreciably above the wilting coefficient. This soil is found to be currently at 6 per cent moisture content. Its osmotic pressure P′ may then be computed as

$$25-2\left(\frac{25-5}{20-4}\right)=22.5 \text{ atmospheres.}$$

The formula for this case then reads

$$AA=\frac{25-22.5-3000(0.00097)}{3000}=\frac{-0.41}{3000}=-0.000137$$

The coefficient of availability being a negative quantity of any magnitude, it is evident that the part of the tree which has been examined can not obtain water from the soil unless (1) the moisture content of the soil is increased, or (2) the foliage may withstand further drying and the creation of a higher pressure, without injury. Under the conditions stated as to the wilting coefficient of this soil, it is still probable that the part of the tree examined may obtain water when it attains a drier state.

In the examination of a tree branch of appreciable length, it may be necessary and desirable to make an additional allowance in h for the horizontal distance, as well as the distance from the ground. This addition, however, would not apply to the calculation of G.

OTHER SOIL PROPERTIES TO BE STUDIED.

ACIDITY AND ALKALINITY.

While neither extreme acidity or alkalinity is often encountered in forest soils, because of their usually good drainage, yet the subject is one that should not be overlooked, even though, on account of its relative unimportance, it must be given rather scant space. Unfortunately because of deficiencies in chemistry itself and a lack of proper understanding of the method by which the activity of acids in the soil might be measured, reliable results in such measurements bearing on problems of plant distribution are only just beginning to appear; for this reason, it is unsafe to say that the concentration of acids in the soil either is or is not an ecological problem distinct from the moisture-supply problems which have just been described. The suggestion of direct toxicity of soluble substances in the soil is frequently encountered, but so far as known no one has shown that toxic effects are not effects produced by the cessation of the water stream. It has also been frequently suggested that active acids or alkalis in the soil combine to withhold from the plant the substances needed for its nutrition. This seems more probable. Skepticism in these matters is designed primarily to indicate that such questions are still open to investigation from more than one angle. The methods for determining acidity and alkalinity in soils will be briefly reviewed, as though these were matters entirely independent of the subject of water supply.

A recent and readily grasped article by Wherry (141) is filled with good suggestions on the vexed question of measuring the acidity of soils, and should be read by everyone who intends to go further with this discussion. Among his suggestions, an outline given by him to cover the various methods of acidity measurement will be followed, with some elaboration, also bringing up at appropriate points the corresponding methods applicable to the determination of alkalinity. It should, perhaps, be explained that the term "alkalinity" is here used in its chemical sense, and not with the broader meaning, sometimes permitted, of total soluble salts.

1. A salt solution is added to the soil. For this purpose there have been used sodium chloride, potassium chloride and nitrate, calcium chloride, nitrate and acetate, zinc sulphide plus calcium chloride, etc. The quantity of acid in the resulting solution, which represents that originally present in the soil plus a much greater amount produced indirectly by the processes[18] outlined is then determined by titration or other means.

In the appendix to this paper has been given in detail the titration method for acidity following the "extraction" of the acids of the soil by potassium nitrate solution, a method which has been much used and debated, but which should probably from now on be considered only for its historical interest. It has many times been found that this method produces appreciable acidity in soils which at the same time evidence alkalinity.

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[18] Briefly, replacement of H-ions in compounds which would in stable condition show no evidence of the weak acids present.

2. No salt solution, but some pure water, is added to the soil.

(*a*) The mixture is titrated with lime water, using either an indicator or observation of the freezing point to determine the end point. This gives the amount of lime needed to neutralize the acid originally present in the soil plus that produced indirectly by the action of lime (which is likely to differ from that produced by a neutral salt solution) as well as the amount of lime required to satisfy the absorptive power of the soil colloids for calcium ion under the given conditions.

The determination of the end point in such a water mixture by the freezing-point method is the method described by Bouyoucos (108), and is based on the fact that as long as the CaOH added is combining with a free acid or an acid salt (which is up to the point of neutrality), the solution will contain fewer and fewer ions, and consequently will have a higher and higher freezing point. When the CaOH molecules begin to remain in solution, however, there is an immediate change in the opposite direction. This method appears to have considerable value, though not wholly a measure of the free acids. Likewise, when the reaction of the solution has been shown not to be acid, through an immediate lowering of the freezing point on adding CaOH, it would seem that the normal freezing-point depression was a measure of the alkalinity.

(*b*) The mixture is filtered and the filtrate titrated with standard alkali. This gives the quantity of acid present in the soil.

By titration with $KHSO_4$ solution, the filtrate may likewise be tested for alkalinity, the method being described in the appendix. It is perhaps desirable to bring out here, however, since both of these methods may be used, that the commonly used indicator, phenolphthalein, does not indicate neutrality, but a specific alkalinity of 30. Wherry suggests the use of litmus of brom-thymol to detect complete neutrality.

(*c*) *The hydrogen-ion concentration* or specific acidity (or alkalinity) is determined—

- *a.* By catalysis of an ester.
- *b.* By measurement of the potential due to hydrogen-ion with the potentiometer.
- *c.* By observation of color changes of indicators whose relations to hydrogen-ion concentration are known.

This last-named method is that which Wherry then describes in detail. It consists primarily of the use of six indicators in various combinations, such that variations between a specific acidity of 3,000 and a corresponding "superalkalinity" may be detected with not too great refinement, yet probably with all the precision necessary in studying the distribution of plants. These extremes correspond, respectively, to hydrogen-ion concentrations of $P_H=3.5$ and $P_H=10.5$.

For the most precise determinations of the degree of alkalinity or acidity the potentiometer is undoubtedly the last word. A number of such instruments are on the market and should require practically no adaptation for the treatment of soil extracts. No reason appears why they might not be readily used in the field. Apparently the apparatus devised by Briggs (111) for determining the "soluble salt content of soils" was of very similar nature, though its relation to hydrogen-ions was probably little understood at the time.

THE MECHANICAL ANALYSIS OF SOILS.

A mechanical analysis of any soil which is being studied extensively is probably worth while if only to give a convenient and approximately correct name for the soil. Thus may be avoided the error of speaking of a soil as a "clay" when, in fact, it contains 80 per cent silt and only a very little clay, or perhaps even a large component of very fine sand and small amounts of the finer materials which make it as stiff as clay. With accumulated analyses of soils, too, comparison will show whether the mechanical analysis of two are very similar, approximately what water-holding capacity a new soil may have, what wilting coefficient, etc. However, in this calculation the humus plays a very important part and its effect is difficult to estimate.

The method of mechanical analysis which may be considered standard has been recently described by Fletcher and Bryan (120). It employs a number of sieves, with perforations of successively smaller size, which separate the particles of various sizes but allow the very fine sand, silt, and clay to pass through. These three grades are then separated in water under the action of gravity.

The standard soil grades recognized by the Bureau of Soils, United States Department of Agriculture, are indicated by the following table of diameters (Table 7), which also indicates the diameters of the circular perforations in the standard sieves. Opposite these values have been set the approximately corresponding sizes of screens which are adapted for handling larger samples in the study of forest soils, under what may be called the "English" rather than the metric system of classification.

TABLE 7.

Class.	Metric. (Diameters of sieve perforations.)	English. (Number of openings per inch.)
	Millimeters.	
Rocks		Less than 4.
Coarse gravel	Over 2	4 to 10.
Fine gravel	2.00 to 1.00	10 to 20.
Coarse sand	1.00 to 0.50	20 to 40.
Medium sand	0.50 to 0.25	40 to 60.
Fine sand	0.25 to 0.10	60 to 100.
Very fine sand	0.10 to 0.05 (settles in test tube in 30 seconds)	Over 100 (settles in bottle in 30 seconds).
Silt	0.05 to .005 (settles in centrifuge in 5 minutes at 800 revolutions per minute.)	Same as metric.
Clay	.005 to 0000 (does not settle in centrifuge; measured by deduction).	Turbid water evaporated and weighed.

The following procedure is suggested as the result of a good deal of experience in treating forest soils:

1. If the soil to be sampled contains a great deal of rock, say over 25 per cent by volume, and of large size, it is desirable to determine the rock percentage by sifting a considerable quantity of the material through a screen having four meshes to the inch. This should be done only when the material is air-dry, and should be accompanied by much beating and brushing to remove the fine material from the rock surfaces. After the process, a sample of about 100 grams of the finer material may be taken. If rocks are few and small, it is better to sample and wash them with the other material, separating them when dry from the coarse gravel on the 2-millimeter or 10-mesh sieve.

2. The sample is placed in a wide-mouth 8-ounce bottle, which is then nearly filled with clean tap water, stoppered, and placed on the shaking machine, or attached to a pulley which is turning at the rate of about 100 revolutions per minute. The amount of shaking necessary will vary from two to eight hours with different soils, but should always be sufficient to break down every lump of whatever size. If the soil lacks gravel for its own pulverizing, place two or three round pebbles in the bottle.

3. The lumps thoroughly broken down, the contents of the bottle are placed on the coarsest screen, with the finer sieves in succession below it, and the whole nest standing over a can of 1 or 2 gallons capacity. The material is washed down through each screen by a tiny stream of water, until all silt and clay have been removed; that is, until the water comes through perfectly clear. The nest of sieves may then be placed in the oven to dry, after which the separation of the sands is readily accomplished by a little jarring of each sieve; the material held on each is weighed promptly, before it can take up moisture from the air.

4. The very fine sand which passes the sieves after drying is placed in the washing bottle. The water from the washing of the material several hours earlier may now be decanted off into a meas-

uring vessel, leaving the very fine sand in the can, some silt and clay, and a little water. This material is also transferred to the washing bottle. As the first measure of liquid in the bottle will be very rich in silt and clay at least one minute should be allowed for the very fine sand to settle. After this time the silt and clay are partially decanted into the measuring vessel. More water is added to the bottle and is thoroughly stirred. With each successive washing the time is reduced, so that as the water becomes nearly clear the sand is allowed just 30 seconds to settle through a 4-inch column of water. It will be noted that the settling is somewhat slower if the water is extremely cold.

5. All the very fine sand is now in the wash bottle, in which it may be dried and weighed, and all of the silt and clay, with a considerable volume of water, in the measuring vessel. It will be economical to obtain the weights of the silt and clay by merely sampling this large volume after thorough stirring. Perhaps 100 cubic centimeters may be drawn off for centrifuging from a total volume of 2 liters. The amount and fineness of the material thrown down in the centrifuge will depend on the time of centrifuging and the speed of the machine. These should be adjusted after repeated trial and examinations of the suspended particles under the microscope. (See Briggs, Martin, and Pearce (117).) However, as the standards for "clay," "silt," etc., are purely arbitrary any investigator may, for his particular purposes, adopt his own, as by deciding on a period of centrifuging which will in every case clear the water of particles of visible size.

The centrifuging completed, the clay water is decanted off into one evaporating dish, and the silt in each tube is washed out with a fine jet of water into another. These are dried in the oven. Care should be used to avoid weighing either the clean dishes or dishes containing this fine material when the general humidity is very high. The amount of silt and clay in the evaporators having been determined, the total amount for the whole sample is readily calculated.

6. The quantities have now been determined in nine grades, and the percentage of the whole which each grade represents may be readily computed. The several percentages may be entered on the form for "Summary of Physical and Chemical Properties of Soil" (p. 134).

It will be noted in the following key that no grade coarser than coarse sand is mentioned. In analyses made by the Bureau of Soils it is customary to pass the material through the 2-millimeter sieve before sampling and to base all calculation on the total weight of this "fine earth"; that is, material not coarser than fine gravel. In forest soils coarser material is too commonly met with to be ignored, and its importance from certain points of view may be as great as that of the soil proper. It is believed, however, to be desirable to describe the soil in such manner as to denote separately the presence of a coarse matrix and a finer soil occupying its interstices. Thus if rocks or gravel formed more than 10 per cent of the mass we might speak of the soil as a "rocky medium sand" or a "gravelly loam." In this event the fine gravel and finer material should be considered as constituting 100 per cent when using the following key:

CLASSIFICATION OF SOILS ON MECHANICAL ANALYSIS.

Soils containing — 20 silt and clay:	
Coarse sand	25+ very coarse sand and coarse sand and less than 50 any other grade.
Sand	25+ very coarse sand, coarse and medium sand, and less than 50 fine sand.
Fine sand	50+ fine sand, or — 25 very coarse sand, coarse and medium sand.
Very fine sand	50+ very fine sand.
Soils containing 20 to 50 silt and clay:	
Sandy loam	25+ very coarse sand, coarse and medium sand.
Fine sandy loam	50+ fine sand or — 25 very coarse sand, coarse and medium sand.
Sandy clay	— 20 silt.
Soils containing 50+ silt and clay:	
Loam	— 20 clay, — 50 silt.
Silt loam	— 20 clay, 50+ silt.
Clay loam	20 to 30 clay, — 50 silt.
Silty clay loam	20 to 30 clay, 50+ silt.
Clay	30+ clay.

THE DETERMINATION OF HUMUS.

The amount of humus in the soil, which plays an important part in the water relations and may also be an important source of nutrients, may be determined in two general ways:

1. By ignition, taking no account of the degree of decomposition of the organic matter, and always involving some error through the evaporation of water which may exist in several forms in oven-dried soils.

2. By extraction of the humified portion of the organic matter with ammonia, and its subsequent ignition.

It should be realized that these two methods produce entirely different results and, in fact, they have distinct purposes. On the one hand, the total organic matter is of interest because of its bearing on the water-holding properties of the soil, and in this connection the total loss on ignition is probably as expressive as any other measure, though in soils containing large quantities of carbonates some correction must be made for their breakdown. It is, however, a misnomer to call this a "humus determination." On the other hand, the amount of humified material is important as a possible source of nitrogen, it being, according to Hilgard (125), "wholly uncertain to what extent the unhumified material will ultimately become humus, from the nitrification of which plants are presumed to chiefly derive their nitrogen."

Loss on ignition.

Loss on ignition, as has been said, may be of interest in connection with water-holding properties. It is readily determined by placing approximately 100 grams of the soil in a shallow earthen or platinum dish, in which it will first be oven-dried and weighed and then heated to red heat in a gasoline or electric oven, with a moderate current of air passing over it. Providing lumps have been broken down at the outset, the oxidation may usually be completed in an hour. After this the sample is again weighed, the ignition loss is calculated, and the percentage of loss is based on the oven-dry weight of the sample.

In the case of soils containing considerable lime or magnesium carbonate, the error through the breaking down of these on ignition may be largely eliminated by a preliminary treatment with dilute hydrochloric acid, as in the humus extraction method.

The ammonia-soluble humus.

The ammonia-soluble humus, or matière noire of Grandeau (122), is the aim of all of the more recent methods of extraction. Lime and magnesia are first removed by washing the soil with dilute hydrochloric acid. Grandeau mixed the washed soil with coarse sand and placed it in a funnel at the bottom of which were fragments of glass or porcelain. The whole mass was then moistened with dilute ammonia and allowed to digest for three or four hours, after which the solution was washed through with water or water containing a little ammonia. The filtrate was then evaporated to dryness, weighed, ignited in a platinum dish, and weighed again. The loss on ignition is the measure of the extractable humus. The residue is termed humus ash.

Hilgard[19] modified the Grandeau method by placing the soil in a paper filter, covering it with a disk of filter paper, and here performing both the acid washing and the ammonical extraction. The latter is accomplished with 4 per cent ammonia water until the filtrate comes through colorless.

Others have attempted to improve on Hilgard's method in order to expedite the process; but, as shown by Alway, Files, and Pinckney (101), they have introduced serious error through including in the ammoniacal extract considerable amounts of colloidal clay which, on ignition, suffers a loss of water. The experience of the writers indicates that the sand filter devised by Grandeau, with also the paper filter used by Hilgard, will come nearest holding the colloids in the soil. Such as are likely to escape will have passed the filter by the time the acid treatment is complete. In the case of the coarser forest soils the addition of sand is wholly unnecessary.

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[19] In Bulletin 38, Bureau of Chemistry, United States Department of Agriculture, 1893.

Alway suggests the recording of the humus ash percentage as well as the humus as a means of detecting the errors which commonly enter into this determination.

CAPILLARY CONDUCTIVITY.

As has been frequently pointed out in the discussion of the moisture problems, the rate at which a plant is able to obtain water from the soil particles with which the roots are in actual contact may have an important bearing on the wilting coefficient for the whole soil mass, and may, in turn, depend largely on the facility with which the moisture travels from one soil particle to another when there is unequal distribution. Thus, a clean sand is generally understood to have the highest conductivity (whether because of the close contact between the particles or because of the clearness of the spaces between the larger particles, is not known), while clay in the soil seems to impede this movement, probably because of absorption, and humus apears to retard the movement, possibly by breaking the contacts between the mineral particles.

The whole subject of capillary conductivity appears to have been thrown into confusion in recent years by practical findings, especially in connection with the study of moisture supplies in the arid farming regions of the West. In brief, it has been found that in certain localities the soil is never moistened to a greater depth than, say, 10 feet, by precipitation; that the moisture which goes beyond the depth of ordinary crop roots is never brought toward the surface by capillary action, and hence is lost for practical purposes; that fallowing with the object of storing moisture in the deep soil is therefore useless.

Buckingham (116) and McLaughlin (132) have apparently made the most exhaustive studies of the movement of soil moisture; and it may be said that these investigations confirm the practical conclusion that when the mean moisture content is very low and the difference in moisture between two points is slight, the rate of movement from the moister to the drier point is negligible. These, of course, are the conditions to be dealt with as the wilting coefficient is approached, and it is somewhat relevant to remark that there is no evidence against the ordinary conception of capillary movement when the amount of moisture in the soil is considerable. It is true, however, that this movement is very slow upward—that is, against the force of gravity.

Considering only that which is particularly relevant to the problem, it was found by Buckingham that considerably different types of soil show about the same capillary flow under the same conditions. A moist and a dry layer of soil were, in these experiments, placed one above the other in direct contact. The amount transferred from the moister to the drier soil in a given time was found to depend almost wholly on their original difference in moisture content; furthermore, the greater part of this transfer was accomplished in a very short time.

A great many methods have been devised for showing the rate of movement of water in soils; but none of these, so far as known, is readily standardized or will produce closely comparable results on duplication with the same soil. This is because the granulation of the soil has an important influence on the capillary forces set up. In view of this difficulty, no procedure can be suggested which is more likely to produce reliable comparative data than the following:

After the completion of the moisture equivalent determination on the centrifugal machine, all water having been extracted which is subject to the force employed (whether this be 100 gravity or 3,000 gravity), and the soil being then in a state of compactness which is somewhat close to a standard, add to the unit volume of soil a small standard amount of water, say 10 cubic centimeters; as soon as this has been absorbed in the surface centrifuge again for short periods until the amount added has been extracted, determining the time for this unit process. This should be a measure of the resistance offered by the soil to the passage of a unit amount of water through a unit distance (the distance may be somewhat variable, but correction may be made directly).

It would be unwise to leave this very open subject without reference to the possibilities of the electrical conductivity method; for, as Buckingham (116) has shown, there is a close correlation between the conditions affecting electrical conductivity and those affecting water conductivity in a given soil. It would seem that there is also a chance for correlation between heat conductivity and water conductivity.

CHEMICAL ANALYSIS FOR NUTRIENTS.

It may be said that almost nothing is known as to the quantitative requirements of most plants for the nutrient materials obtainable from the soil with the soil water, and little enough as to the elements which in greater or less quantity are essential for growth. The lack of knowledge with respect to trees is especially glaring,[20] little attention having been paid to the subject because of the almost universal belief that the requirements of trees are satisfied by almost any soil. That this is probably true of such trees as the pines is evidenced by their adherence to light, sandy soils. In fact, rather low requirements may be assumed for all of the evergreens on theoretical grounds, because of the fact that the green, functioning parts are of long life and the main product, cellulose, is a purely organic compound.

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[20] The writers do not consider the evidence obtained by the examination of leaf ash and other similarly crude methods, even as convincing evidence of qualitative requirements.

Ecologically speaking, evidence of any direct part played by soil fertility in the distribution of species, and especially of forest trees, is rarely found. This may be partly explained by the fact that forest soils are usually young and potentially fertile, so that other characteristics, especially water-holding capacity, come into greater prominence. Much careful work must be done, however, to determine where and when soil fertility becomes an important ecological factor.

Much difference of opinion exists as to how the fertility of the soil should be measured. There is potential fertility in practically all of the soil mass except the silicon, and actual available fertility only in those substances which are currently in solution with the soil water. As has been pointed out, notably by Hoagland (127), the quantity of all substances in solution varies not only with the drain upon these substances by plants, but with the quantity of the soil water. For practical purposes these substances may be said to be soluble only to a limited extent.

The ordinary complete quantitative analysis of a soil involves the treatment of all of the mass susceptible to chemical action, with a view to discerning potential fertility. In some young soils, especially if formed in situ, these potentialities may be arrived at by the experienced person through examination of the mother rock. Where there is any question, however, the ordinary investigator, because of the great amount of equipment and technique involved, should refer samples for analysis to some well-equipped laboratory, such as that of the Bureau of Soils in Washington. Four or five pounds of the soil are required for complete anaylsis. The samples should be thoroughly air-dried when taken from the ground, freed of rocks, and shipped either in jars or in heavy canvas sacks from which the fine material will not be lost.

To obtain a measure of the total soluble salts readily available in the soil solution, where the chemical make-up of the soil is generally known, or may be assumed to be adequate for all needs, extraction of the solutes by leaching may be employed. For comparative purposes, the amount which may be extracted with five volumes of distilled water (1 liter for 200 grams of soil) will serve as well as a more thorough extraction. The soil is placed on a paper filter, in a 6-inch funnel, and the water is poured on to it, a few cubic centimeters at a time, through a period of 24 hours. Before the soil has thoroughly settled, some clay is likely to pass through the filter. This is eliminated by pouring on to the soil a second time the first 100 cubic centimeters of water which passes through. When all of the water has drained out, the solution may be partly boiled away and allowed to cool, when the suspended matter will largely flocculate and may be removed by a second filtering. The clear solution is then evaporated in a weighed porcelain dish. Solutes varying in amount from 20 to 1,500 parts per million of the soil weight are ordinarily found in such extracts.

This subject has been investigated in great detail by King (129).

For the purpose of ecology, qualitative analyses showing the presence in some quantity of the elements and compounds known to be essential, may often be all the chemical evidence that is required to throw the burden upon some other environmental condition. Following Osborn (135), who has rather recently given a summary of the evidence on this subject, the investigator may look for:

1. Nitrogen (in the form of nitrates), as an essential constituent of proptoplasm, required in large quantities when the proteins are being produced, as in seed formation. Nitrogen is itself practically useless without nitrifying agencies in the soil, so that the presence of humus is not absolute proof of the abundance of nitrates. Nitrogen in certain forms may also, as shown by Schreiner and Skinner (138), inhibit plant growth. This is a subject of great complexity.

2. Phosphorus, as an essential of the nuclei of cells.

3. Iron, as an essential of protoplasm, and playing an important part in the formation of chlorophyll. A lack of iron in available form is quickly shown in yellowing or " chlorosis " of foliage.

4. Magnesium, as a constituent of the chloroplasts.

5. Sulphur, required for forming proteins.

6. Potassium, probably as a regulator of life phenomena through chemical reactions.

7. Chlorine, commonly present in plants and probably functioning in metabolism.

It is with a view to detecting the lack of some of these substances that the following simple tests are enumerated, requiring the minimum of laboratory equipment and technical skill.

The sample of air-dried soil which is to be examined should be placed in a glass jar and distilled water added to the amount of five to eight times the volume of the soil. After about five minutes the solution may be used.

One hundred cubic centimeters of the solution may be tested qualitatively for chlorine. For this purpose, to the soil solution should be added one or two drops of potassium chromate ($K_2Cr_2O_4$) solution and titrated from a dropper by a weak solution of silver nitrate ($AgNO_3$). If chlorine is present it will be precipitated as silver chloride. The test for chlorine can be made also more simply by taking some of the soil solution in a test tube and adding silver nitrate solution.

For tests of the presence of other chemical substances which may be of importance in the life of plants, the following procedure is suggested:

Three hundred cubic centimeters of the soil solution are poured into a porcelain dish and slowly evaporated, the drying being continued almost to red heat in order to burn any organic matter. If the organic matter is not burned up in the porcelain dish containing the dry residue, aqua regia is added and the liquid evaporated to dryness at least twice. The residue is then heated to red heat in order to render the silicic acid insoluble. The soluble residue is dissolved by heating in a weak solution of hydrochloric acid, and the liquid is filtered off from the white amorphous residue of the acid. The filtrate is collected into a graduate and water is added to bring it up to 300 cubic centimeters. Of this the following amounts are taken for further tests:

1. One hundred cubic centimeters for determining the entire amount of Fe_2O_3 (ferric oxide)$+P_2O_5$ (phosphorus pentoxide)$+$ Al_2O_3 (aluminum oxide)$+CaO$ (calcium oxide)$+MgO$ (magnesium oxide).

The solution is neutralized with sodium carbonate (Na_2CO_3) until some cloudiness appears, then from 5 to 10 cubic centimeters of sodium acetate ($NaC_2H_3O_2$) are added and the solution is heated; the entire amount of ferric oxide and aluminum oxide will be precipitated in the form of basic acetates. These are filtered off. The filtrate is heated and neutralized with ammonia (NH_3) until an alkaline reaction is obtained, then 1 or 2 cubic centimeters of ammonium chloride (NH_4Cl) and ammonium oxalate $(NH_4)_2$ $(COO)_2$ are added. The calcium is precipitated and is filtered off.

To the filtrate, after it has been cooled off, are added several cubic centimeters of sodium ammonium phosphte (NH_4NaHPO_3), and it is left to stand for several hours. If magnesium is present it will be precipitated.

2. One hundred cubic centimeters for determining SO_3 (sulphur trioxide).

For this determination the 100 cubic centimeters are heated and to the solution are added several drops of barium chloride ($BaCl_2$). If SO_3 is present, it should precipitate in the form of barium sulphate ($BaSO_4$). If it is not precipitated at once, the solution to which barium chloride has been added is left to stand for several hours.

3. One hundred cubic centimeters for determining P_2O_5 (phosphorus pentoxide).

In order to determine the presence of phosphorus pentoxide (P_2O_5), 100 cubic centimeters of the solution is neutralized with ammonia until an odor is perceived, the solution is made acid by the addition of weak nitric acid (HNO_3), and to such acid solution there is added from 10 to 15 cubic centimeters of molybdic acid (H_2MoO_4).

A qualitative test for ferric oxide can be made in the water solution of the soil by hydrochloric acid. Some hydrochloric acid is added, together with several drops of potassium sulpho cyanide ($KSCN$). A pink, or often bright red, color will indicate the presence of ferric oxide in the solution. When the soil is rich in ferrous oxides, their presence can be readily ascertained by dropping directly upon the soil some of the potassium ferricyanide ($K_3Fe(CN)_6$) solution which with the ferrous oxides gives a blue color.

The form for the " Summary of Physical and Chemical Properties of Soil " is provided with a number of blank spaces in which the results of qualitative or quantitative tests for various salts may be entered.

Form 2.

[U. S. Forest Service, Physical Survey.]

SUMMARY OF PHYSICAL AND CHEMICAL PROPERTIES OF SOIL.

Type ——— ————: *Station No.* ——; $\left.\begin{matrix}\textit{cover}\\\textit{open}\end{matrix}\right\}$ *mark out one; examined, date* ———————— *19*—: *by* ————————

Forest ——; Project ——.

FIELD EXAMINATION.

Total depth of permeable soil ——— feet; proportion of soil space occupied by rocks; soil, ———%; subsoil, ———%
Geologic origin and age of soil (1)....................
Drainage conditions indicated by topography: Slope ———%; aspect ———; elevation above Water table level (2), ——— ft.
Drainage conditions indicated by sub-soil ———
Evidence of leaching or salt accumulations (3), ———.
General texture of soil, fine or coarse, sticky or friable, swelling or settling with moisture. Color (4).
Humus: Depth of surface litter ——— inches: Penetration of humus in mineral soil, as indicated by color ——— inches. (This indicates depth of "soil" as distinguished from "subsoil.")

HUMUS CONTENT BY TEST: Method used (5).

Surface.......... ———% ....ft., ———%, ...ft ———%, ...ft., ———%, ...ft. ———%:

MECHANICAL ANALYSIS: Method used (6).

Made by ————: Date ————

Depth	Rocks %	Coarse gravel %	Fine gravel %	Coarse sand %	Medium sand %	Fine sand %	Very fine sand %	Silt %	Clay %	Total weight sample examined	Other Data (Give Standard (Bur. of Soils) name based on Analysis) (7)
Surface................	....	....	....	....	....	....	....	....	....	....	
....ft................	....	....	....	....	....	....	....	....	....	....	
....ft................	....	....	....	....	....	....	....	....	....	....	
....ft................	....	....	....	....	....	....	....	....	....	....	
....ft................	....	....	....	....	....	....	....	....	....	....	

PHYSICAL ANALYSIS: (8).

Made by ——————: Date ——————

Sample Nos.	Depth and source	Saturation capacity (S) %	Capillary (9) capacity (C or Cl) %	Moisture (10) equivalent %	(C Cl)(11) ratio	Nonavailable water (12)(N or Nl) %				Density %	Permeability (13)				
											Inch, rate, minutes			Total time minutes	Total absorption inches
						%	Date	Species	Method		1st inch	2d inch	3d inch		
....	Original soil, surface...														
....	Original soil, ...ft....														
....	Original soil, ...ft....														
....	Original soil, ...ft....														
....	Original soil, ...ft....														
....	Soil in well..........														

CHEMICAL ANALYSIS.

Made by ——————: Date ——————

Depth	Total soluble matter (14) %	Alkalinity (15) %	Acidity %	%	%	%	%	%	%	Insoluble matter %
Surface........										
....ft........										
....ft........										
....ft........										
....ft........										

SUMMARY OF SOILS DISCUSSION.

The preceding discussion has attempted to bring out the theoretical considerations which make the study of soils very important in forestry, from the standpoint of initiation of seedlings, later competition between individuals and species, and the rate and ultimate limit of height growth on any particular site. In the main all other soil conditions have been considered in their bearing on the supply of soil moisture. In view of the length of the discussions, it would appear desirable to repeat the salient points, as follows:

1. It is believed that from every ecological aspect the important soil condition is the availability of the soil moisture.

2. Plans for the study of this soil condition have been based on the assumption that the relation between the plant and the soil in which it grows can best be demonstrated if, at any time, the status of either may be expressed in terms of osmotic pressures.

3. The generally coarse character of forest soils, and the presence of rocks which are as characteristic as any other part of the soil and can not properly be eliminated, give rise to the need for special methods of examining forest soils, and particularly for methods adapted to larger samples of the soil than have commonly been used in agricultural investigations.

4. The total moisture of the soil, while not directly making possible the comparison of sites, if there be any variation in soil composition, must be had for most of the indirect methods of comparison; and in forest studies it must be determined periodically through one or more seasons in order to discover the conditions that are critical. The quantity may sometimes be found through ordinary methods of sampling and drying the soil samples: but often, because of mechanical difficulties, and to insure greater physical uniformity in the samples from time to time, it is desirable to have "wells" of prepared soil from which successive samples will be taken.

5. If it seems desirable to compute the moisture of the natural soil from that found in a soil well, this may be done, at least approximately, by comparison of the capillarities, moisture equivalents, and wilting coefficients of well soil and natural soil, respectively. It seems probable, however, that up to a high moisture content osmotic equilibrium is more likely than capillary equilibrium between the well and the natural soil, so that if the moisture of the former may be expressed in terms of osmotic pressures, it is unnecessary to compute the moisture of the soil.

6. For any study of the critical situations in soil moisture, either for seedlings or for older trees, it is necessary to know the wilting coefficient of each soil under consideration. The moisture content at which a plant may wilt, however, varies widely not only according to

physical properties of various soils, but also, for any given soil, according to the manner in which the test is conducted, the age and species of the plants employed, and, more important still, according to the atmospheric conditions at a time when the moisture supply is running low. In short, the wilting coefficient is dependent vary largely on the rate at which the plant must obtain water in order to balance losses. As the atmospheric conditions are difficult to control, and practically impossible to reproduce from time to time and place to place, it follows that wilting coefficients are empiric quantities and have no precise value.

7. It is probably very desirable that wilting tests should be continued as a further check upon theory, and for the further establishment of relations between different species and different soils. Relative values for different species and soils, of much value and interest, are to be obtained through simultaneous tests at any given point, and by such comparisons a scale of values either for soils or for species may eventually be built up. There are, however, indirect methods of arriving at the wilting coefficient which are not only desirable for practical purposes, but will add greatly to our understanding of the variations in wilting coefficients due to biological and environmental factors.

8. The study of the freezing of soil water, the study of the acquirement of moisture by soils when exposed to saturated vapor, and even the behavior of the soil water when subjected to an external mechanical force, all point to the fact that water may exist in the soil as a liquid, capable of more or less movement from one soil particle to another, or as a vapor;[21] that is, as separate water molecules, held in place by the affinity of the solid particles, and thereby prevented from moving. All signs, too, point to the fact that, except possibly in soils of unusual alkalinity or acidity, the soil water is truly nonavailable only when it ceases to function as a liquid. While wilting of plants may often occur with liquid water still available, this is readily accounted for by the slow rate of movement toward the roots, which become a probability, especially in clay and humous soils, whenever the volume of water is not large. Water obviously moves much more readily in coarse than in fine or humous soils; and, as has been mentioned, the rate which may be fatal to a plant depends on the needs of the plant as determined by its losses.

9. While, therefore, no method has yet been devised by which the theoretical and exact wilting coefficient may be directly arrived at, any one of the methods mentioned in the preceding paragraph has its

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[21] It would, perhaps, be more descriptive of the kinetic status to speak of this as "solidified water" and it is not certain that a wide separation of the molecules, as in vapor, is an essential part of the situation.

possibilities as an avenue of approach. Thus, by the freezing-point method the osmotic pressure of the soil solution corresponding to any given moisture content may be determined; and by several trials, the point at which the soil water ceases to behave as a liquid, that is, ceases to show a definite freezing point, may be determined quite closely. This water content is probably the term sought as a standard. The freezing-point method has one serious objection: namely, that it forbids keeping the soil during test in a natural state of compactness, or with a natural arrangement of the soil particles.

The vapor transfer method has also many possibilities. In the ordinary determination of the hygroscopic coefficient the water vapor is probably not entirely saturated; and, in consequence, under certain empiric conditions of the test, there may be obtained in a limited time a limited absorption of vapor by the soil which was air-dry at the outset. The quantity absorbed, so far as the tests go bears a fairly constant relation to the wilting coefficient, the ratio of the two quantities being approximately 2:3. The objection to this method is that the conditions are purely empiric, and the quantity of soil treated is very small.

By exposing soils to water vapor in a vapor-tight chamber, such as a bell jar, and in the presence of a solution of an active salt which represents a given osmotic pressure and vapor pressure, considerable masses of soil may, after a long period, be brought to vapor pressure equilibrium with the solution and with one another. The moisture content of each soil is then the "osmotic equivalent" of the control solution, whose osmotic pressure is readily calculated. The osmotic pressure to exist at the end of the test may be in part controlled by calculations at the outset, and later by changing the control solution. A solution, at the end of the test, representing 50 atmospheres osmotic pressure, for example, might be taken as a standard for establishing osmotic equivalents in lieu of wilting coefficients. The objections to this method are the long time required to complete a test and the absolute need for a constant temperature, or at least for the elimination of rapid changes. The former objection is partly counterbalanced by the number of soils which may be treated simultaneously.

In the moisture-equivalent determination, as so far conducted, the moisture of any soil is submitted to a definite centrifugal force which tends to separate it from the soil. Within the limits of agricultural types of soil, at least, the force of 1,000 gravity employed by Briggs and Shantz (114) appears to leave in the soils amounts of water which bear a nearly constant relation to the respective wilting coefficients. Experiments with a force of 100 gravity have shown wide variations in results with different types of forest soils, indicating that, as humus and clay proportions vary, both strong and weak capillary tensions are set up, and these do not react in the same way on relatively large and very small quantities of water in the soil. It appears, therefore, as suggested by Free (121), that the effective procedure is the employment of a variable force, sufficient in the case of any particular soil to extract all of the water which is extractable. It seems probable that this quantity would correspond to all of the liquid water capable of moving from one part of the soil to another. The remaining water would probably correspond closely to the "unfree water" of Bouyoucos (106) and what in this bulletin is termed "water vapor," or water whose molecules are too rigidly held by solid substances to have the motility of liquid molecules. While this method is as yet untried and would obviously be more laborious than the present standardized procedure, possibly presenting new mechanical difficulties, it promises so much as a direct and rapid means of determining a physical constant that it deserves serious investigation. In the meantime the 1,000-gravity test should be employed as the basis for comparing the moisture conditions of various soils and in the detailed study of their wilting coefficients.

10. Once the wilting coefficient of a soil has been determined, directly or indirectly, the current moisture condition may be expressed in terms of the percentage of available moisture or the available moisture per unit of soil volume, by subtracting the nonavailable moisture from the whole. The amount of water per unit of volume recommends itself particularly in comparing the conditions of open and dense forest stands, provided that the root extent of the individual tree has been investigated. Without such information, very wrong conceptions of the moisture supplies available to the individual trees in different forest types are likely to be formed.

11. For the purpose of expressing the condition with which any individual plant is coping, particularly the conditions against which a seedling must struggle in times of drought, it is very desirable to reduce the water content of the soil to terms of availability. If it is assumed that the wilting coefficient stands for a definite osmotic pressure in the soil, with which the osmotic pressure in the plant is in equilibrium (this, of course, being only approximately true, as pointed out in paragraph 6, and being further subject to the conditions of the plant, as indicated in the following paragraph), then, when the moisture content is equal to the wilting coefficient, the availability of the soil water is 0.

When the moisture content of the soil is twice as great as the wilting coefficient, about twice the osmotic pressure may be expected in the plant as in the soil, and this should make possible a fairly definite rate of absorption by the plant. The availability at this point may be called 0.50. Similarly, when the moisture content is three times the wilting coefficient, the availability may be expressed as 0.67. It should be understood that these are arbitrary terms, and that they only express relatively the conditions under which a given plant in a given soil may be obtaining its water from time to time, perhaps a little more clearly than these conditions can be expressed through the percentage of available water.

12. Finally, the plan of expressing the relation between the plant and its moisture supply currently and accurately through the osmotic pressure of each has been conceived. The difference in osmotic pressure in favor of the plant expresses the degree of control of the plant over its water supply; but, since the highest osmotic pressure in the plant is likely to be attained at that point which is farthest from the roots, where also the danger is greatest, it is evident that in considering the availability of water to this point there must be considered the distance through which the differential pressure must operate; or, in other words, the osmotic gradient, say, per centimeter of stem tissue, etc. This gradient will also be affected by gravity. As the coefficient of availability, therefore, a term has been proposed which brings these elements into their proper relations with definite values. Thus,

$$AA = \frac{P - P' - G}{h}$$

a formula which promises to be especially enlightening in studying the phenomena of growth in older trees, as they compete with one another and reach their limits of height for a given site. The value of AA is seen to fluctuate with each change caused by water loss or accretion in the region where P is determined, as well as with gradual changes in the conditions of the soil moisture.

13. The discussion has included other aspects of the soil, which, with the possible exception of nutrition, it is believed should be considered only as indicator aspects; that is, these aspects will only serve to explain the phenomena of soil moisture. They include alkalinity or acidity, humus content, composition (as indicated by the sizes of the soil particles), and the capillary transporting power of the soil.

14. In the study of seedlings during their most critical periods of establishment—this being the period when the character of the plant society is most largely determined—it is believed that the percentage of available moisture within reach of the usually short roots is of primary importance. To determine this with any accuracy will be found difficult on account of the usually heterogeneous character of the soil layer that will be involved. The proper study requires:

(*a*) Determination of root depth at each examination. It is through this determination that a distinction between species may be made.

(*b*) Selection of the soil sample at the point of maximum moisture content within the zone reached, which, of course, in the important periods of drought, will usually be the deepest point reached.

(*c*) Determination of whole moisture of each sample.

(*d*) Determination of moisture equivalent of each sample, at least as a means for classification of unlike samples.

(*e*) Retention of samples, with determinations of wilting coefficients on typical classes, probably after the period of field observations. In these determinations it will be well to compare the behaviors of the two or more species involved.

It is believed that, with tiny seedlings, the quantity of water usually required to maintain life is so small that the available volume may be left out of consideration. In other words, the samples may be practically point samples, seeking always the maximum available. Even this painstaking examination of soil moisture, however, may be futile without a record of the conditions conducive to water loss, particularly the temperature conditions at the surface of the soil.

15. Whenever, in a plant society, competition between individuals of the same or different species becomes a factor, the moisture problem is different from that which confronts seedlings. In the forest there may be competition for moisture without keen competition for light, but the two will usually be closely interrelated. In any ordinary situation the keenest competition for moisture occurs near the end of the growing season, when the reserve winter moisture has been exhausted and the current rate of use is in excess of the current accretion. Where this is the case the study of soil moisture may be restricted to a period of two or three months in the late part of the season.

It is evident that, of two individuals on the same site, one may possess an advantage over the other through deeper rooting. It is therefore essential in each site studied to know the extent and depth of the roots of the plants under observation, and to sample the soil for moisture in accordance with a root map.

If it should appear that two individuals in competition have essentially the same moisture supply, then it obviously becomes necessary to determine their respective relations to that supply by examination of their internal conditions as affected by atmospheric conditions, light, etc. It is not sufficient in these circumstances to say that soil moisture is not a factor in the greater success of one than of the other. By measuring the osmotic pressures of the plants it may be found, for example, that the individual which is most exposed to light, wind, and other desiccating influences has a greater control over soil moisture than the near-by individual which is shaded and protected, and which, nevertheless, may die from the effects of drought while the other thrives. Unless, then, it is desired to deal in generalities, and ascribe to one species certain characters which another does not possess, on the basis of general knowledge or pure assumption, it will be necessary in studying competition to go to the whole length prescribed for the determination of the coefficient of availability.

16. Much the same situation exists with respect to the study of the final character of the forest formation, its height, rate of growth, etc. The critical study of the moisture conditions in relation to ultimate height is of special importance in forestry because ultimate height, in forest management plans, is often taken as a criterion of the quality of the site; that is, its yield possibilities. Are the two things closely related? If the ultimate height is limited by drought conditions which occur only periodically, may not the yield possibilities be considerably greater or less than would be indicated by this measure, depending very much on the total water-holding capacity of the soil, etc.? Obviously such questions as these can be answered only after exhaustive study. This requires the establishment of permanent soil-moisture stations, the determination each year of the critical conditions that exist, and the use of the entire system that has been suggested for arriving at a measure of the true conditions.

SPECIAL EQUIPMENT FOR SOIL MOISTURE AND SOIL QUALITY STUDY.

Soil sieves:	
Standard soil sieves. Per set, about	$10.00
Soil borers:	
3-foot soil borer, tube, with hammer	9.00
6-foot soil borer, tube, with hammer	11.00
6-foot soil borer, auger handle hammer	12.00
Soil cans:	
Patent seamless, noncorrosive, tin soil cans—	
4-ounce can, deep style, per gross	3.50
8-ounce can, deep style, per gross	4.00
(35 per cent discount on above prices to United States Government.)	

Soil sample cans, seamless tin, No. 9178 A—

Capacity, ounces	4	8	16
Per dozen	$0.22	$0.33	$0.55

Soil sample cans, aluminum, with screw tops—	
2¼ inches in diameter by 2½ inches high, unnumbered 9183, each	.25
With can cover numbered. (In ordering, state what numbers are desired.) No. 9183 A, each	.30

Soil sample can, aluminum, with aluminum top. The diameter of these cans is uniform, so that the cover fits the bottom of the can, Soil cans—Continued.

making it possible to keep can and cover together while the can is open—

Number	1	2	3
Diameter, inches	2	$2\frac{1}{2}$	$3\frac{1}{2}$
Height, inches	$\frac{7}{8}$	$1\frac{3}{4}$	2
Each	$0. 11	$0. 15	$0. 20
With can and cover numbered. (In ordering, state what numbers are desired.) No. 9184 A, each	$0. 16	$0. 20	$0. 25

Aluminum soil cans, $2\frac{1}{4}$ by $2\frac{1}{2}$ inches, with screw tops—	
Lightweight, per hundred	$38. 00
Heavyweight, per hundred	45. 00
Cans, galvanized, 4 by $5\frac{1}{2}$ inches, for capillarity, moisture equivalent, etc. (Any sheet-metal works.)	. 40
Drying ovens:	
Hot-water bath, in various dimensions from 9 inches up	About $50. 00 and up.
Electric, Freas, type R No. 108, inside dimensions 16 by 14 by 16 inches, thermostat, thermometer, etc	$210.00
Hearson low temperature incubators, gas and electric heated, various sizes	140 to 360. 00
Potentiometers and other electrical resistance apparatus.	
Water-retention cup, for determining the maximum water retained by soil, of brass 2 inches in diameter by $\frac{7}{8}$ inch high, with diaphragm of perforated metal fastened about $\frac{7}{16}$ inch below top, No. 9295	0. 20
Capillary moisture pans:	
Hilgard's small circular metal pans, about 1 centimeter high and $4\frac{1}{2}$ inches in diameter, with perforated bottoms for determining "capillary moisture" of soil, each	1. 25
Per ten	10. 00
Balances, glassware, reagents, etc. (Obtainable from all dealers in laboratory supplies.)	

ATMOSPHERIC HUMIDITY.

The humidity of the atmosphere is directly reflected in any such water-containing object as the leaf of a plant, in which there is a constant tendency to come into vapor-pressure equilibrium with the atmosphere, usually through evaporation but in rare circumstances through absorption. The point of equilibrium between the leaf and the atmosphere will be better understood by considering the discussion which has preceded, in reference to osmotic pressures.

Although this constant tendency is nearly always causing the loss of water from plants, the humidity of the atmosphere alone can not be taken as a measure of the "evaporation stress," or rate of evaporation, depending on the wind movement which aids in diffusion of vapor, and the heat supply, principally from sunlight. For this reason, when a direct measure of the evaporation stress is possible through the use of some form of atmometer, ecological studies will not require the measurement of atmospheric humidity except in a somewhat perfunctory manner, as a means of detecting errors in evaporation records, or possibly for comparing conditions locally studied with stations for which there is no evaporation record, but which maintain a complete record of wind movement, sunshine duration, and humidity. In such an event it may be possible to work out a fairly constant relation between the evaporation from any given type of atmometer, and a combination of these other conditions, properly integrated, in the general relation of:

$E\ (K) = $ (Wind movement plus saturation deficit) sunshine.

The term "vapor pressure" expresses the weight per cubic foot, or the pressure, in centimeters of mercury, of the vapor currently in the atmosphere. The term "saturation deficit" expresses the lack of vapor pressure, or the difference between the existing vapor pressure and that which the atmosphere would contain at the current temperature if the space were saturated with water vapor. The "dew point" indicates the temperature at which the existing vapor would condense; or, in other words, the temperature at which the existing vapor would produce a condition of saturation. It is readily seen, then, that the saturation deficit is the difference between saturation pressure for the current dry-bulb temperature, and saturation pressure for the temperature of the current dew point. The term "relative humidity" expresses, as a percentage, the relation between the existing vapor and that which might be present if the space were saturated at the current air temperature.

The dew-point figure is used only incidentally in computing vapor pressure, saturation deficit, or relative humidity. Of the three, experience in a number of forest ecological studies has shown that the saturation deficit is by far the most useful, giving, as it does without further reference to temperature conditions, a direct measure of the capacity of the atmosphere for more vapor, and hence, in some degree, a measure of the rate at which evaporation will take place.

The psychrometer, consisting of a pair of thermometers mounted on a frame in such manner as to be readily whirled in order to accelerate evaporation, is the common instrument for determining atmospheric humidity. One of the thermometers is covered with a layer of cloth (preferably linen), which is dipped in clean water before making the exposure. The evaporation of this water cools the thermometer, or, as the expression is, causes "a depression of the wet bulb;" and the maximum depression which it is possible to produce by vigorous movement of the instrument through the air, taken with the current temperature, is considered to give a measure of the atmospheric humidity. Tables have been worked out, after experiment, for almost all possible combinations of air temperatures and wet-bulb depressions, showing the corresponding dew points and relative humidities. Of these the best-known in this country are the "Psychrometric Tables" of the United States Weather Bureau, contained in its Bulletin 235. These have been worked out for barometric pressures of 30, 29, 27, and 23 inches. In accordance with American custom, vapor pressures are given in inches of mercury. Through the courtesy of the Weather Bureau, it is possible to produce in the Appendix an additional Table of vapor pressures for a mean barometer of 21.42 inches, prepared by B. C. Kadel for the special use of the Wagon Wheel Gap Experiment Station, at an elevation of 9,300 feet. This table will doubtless be of considerable assistance in ecological studies in the western mountains.

The vapor pressure may also be determined very quickly and precisely by means of dew-point apparatus and a table of saturation pressures corresponding to various temperatures. This apparatus is, however, far less convenient for field use than the psychrometer.

The ideal record of humidity is, of course, one which shows the atmposheric condition for every hour of the day. Theoretically, this is obtained by the use of the hair hygrograph; but, actually, the instrument is of very little use.

The atmospheric conditions are measured in terms of relative humidity, which fluctuates rapidly with every change in air temperature. The record must then be transposed, in conjunction with the continuous temperature record, into terms of absolute humidity and saturation deficit, before it can have much value. Furthermore, the hygrograph is probably the least reliable and accurate of the automatic instruments commonly used.

Since the absolute humidity or vapor pressure usually does not change through a wide range in a short time, but shows a general tendency to increase as the air warms and to decrease with the cooling at night, it is possible to determine a fairly satisfactory mean humidity for any day (except of course during general disturbances) by means of two or three observations with the psychrometer. For example, the hours of 7 a. m., 1 and 7 p. m., have been used, or 7 a. m., 2 and 9 p. m. After hourly observations for a few days at any season and point, it should be possible to select one or more convenient hours when, in the ordinary sequence of events, the mean humidity of the day may be approximately measured, either at each observation, or through averaging unlike valuations. As has been suggested, the absolute humidity varies less than the relative humidity or saturation deficit. Therefore, for calculating the mean saturation deficit for the day it is logical to arrive first at the mean vapor pressure, and then, after calculating the mean temperature for the whole period, to obtain the saturation deficit by deduction.

If only one psychrometer reading a day is feasible, both the wet and the dry bulb reading may be entered in the first columns of the "Humidity, Wind, and Evaporation" form, and the relative humidity, vapor pressure, and saturation deficit calculated therefrom may be set opposite. When several readings are made each day, it is suggested that the calculated vapor pressures be recorded on the form for "Hourly (Air, Soil, or Actinograph) Temperatures" for their appropriate hours, and that only the mean vapor pressure be recorded on the "Humidity, Wind, and Evaporation" form.

The relative humidity, vapor pressure, and saturation deficit should be averaged by decades and months. The means by months, the year, and the growing season, should be shown on the annual "Summary" form.

INSTRUMENTS.

Psychrometer, sling, standard Weather Bureau pattern; aluminum backs; polished hardwood handles; double-length connections; 2 glass tubes, exposed, mercurial thermometers, 9 inches long; stem-graduated and figure on glass for each 10 degrees; Fahrenheit or centigrade	$3.00–$6.00
Whirling apparatus, stationary, complete (without thermometers)	18.50
Cog psychrometer, Thermometers about 4½ inches long, reading —5° to 50° C., No. 1230	4.50
Hygrograph (or self-registering hygrometer) complete with a year's supply blank forms. No. 58–B, pen and ink	80.00

WIND MOVEMENT.

Wind movement may be effective upon plants both directly and indirectly; that is, through mechanical breakage, windfall, etc., and through its influence upon evaporation and transpiration.

While mechanical injury to trees by wind seems to be a less important factor in American forests than in those of Europe, judged by the literature on the subject, the problem of windfalls is one of ever-growing importance as forestry is extended and thought is given to the conservation of that portion of the stand which is not now merchantable or is needed as a guarantee of future reproduction. A recent article by Weidman (150) and several other articles that might be cited have shown the importance of the problem and the desirability of a great many more wind records than are now available for our forest regions, if the problem is to be scientifically solved. Perhaps this is a far cry from ecology. Yet a disturbance in the forest which is capable of starting a new succession is certainly of some ecological significance, at least after it has occurred.

Wind movement has without doubt a very marked effect on evaporation; and, in addition, the moving air may be either a source of heat or a means of dissipating the heat of sunlight, as suggested by

Bates (145) in discussing the actual measure of heat available for use in the plant. The first of these influences may be practically ignored, as was the case with humidity, if there is available a record which has integrated all the factors in evaporation. It is believed, however, that most ecological studies will be found deficient if the record of wind movement is not obtained.

To obtain a record of wind movement in the forest which may cause mechanical injury, the anemometer should undoubtedly be placed almost at the tops of the tree crowns, where the most severe winds will be encountered. A strong support is needed to prevent loss of record at the most critical times.

In the study of reproduction and of other shall plants, it may even be necessary to dig a pit for the stem of the anemometer in order that the cups may be close to the ground surface.

The standard Robinson anemometer is the most practical instrument for all outside work. Because of a friction factor, it underrates wind of low velocity such as is often characteristic of the forest floor, and slightly overrates the high velocities. The amount of wind movement may be read on the dial of the instrument to tenths of miles, and the anemometer may also be electrically connected to a register so as to give a record of each mile of wind movement. Because it records no less than a mile of wind movement, the Robinson anemometer is not wholly satisfactory from the standpoint of mechanical injury to trees. It is possibly more true in mountainous regions than elsewhere that the winds of greatest velocity are gusty, and it seems likely that the gusts of only a few seconds' duration may have at least twice the mean velocity recorded for whole miles. While daily or more frequent readings of the anemometer dial may be sufficient where a definite use of the wind record can not be foreseen, in many cases the occurrence of maximum and minimum velocities, the movement by day and by night, etc., as obtainable from the electrically operated register, will be desired. Since the current required for operation is only 2 or 3 volts, connection with the anemometer in the field may be made with the crudest sort of conductors, using wire fences, or insulated wire laid on the ground. In this way the register may be in a protected place and receive due attention.

Apparently the only apparatus capable of recording momentary high velocities is the Dines pressure-tube anemometer, the use of which in the forest is hardly feasible.

Wind vanes with connections and registering device are obtainable, and may possibly be desired at one station in a locality. There is, however, no ecological significance in wind direction: and if there were, it is probable that a single observation on prevailing direction each day and night would be amply sufficient.

Form 8.

[U. S. Forest Service, Physical Survey.]

HUMIDITY, WIND, AND EVAPORATION.

Type ——————; *Station No.* ——; *cover* / *open* } *cross out one;*
Month of —————— *19* ——

(Elev. of Anemometer ....)

(Elev. of Evaporimeter ....)

Date.	Humidity.					Wind movement.									Evaporation[3] (by ....). (Water or non-freezing solution.)					
						Velocity.			Prevailing direction.			From hourly record[2]								
	Dry bulb.	Wet bulb.	Rel. hum.	Vapor press.	Sat. def.	Time of ob.	Dial.	Movement.[1]	Day.	Night.	24 Hours.	Max. Mov't 1 Hr.	Day Mov't.	Night Mov't.	Read.	Water loss.	Re-filled to.	Read.	Water loss.	Re-filled to.
	F°	F°	%	Ins.	Ins.	Hr.	Mi.	Mi.	Dir.	Dir.	Dir.	Mi.	Mi.	Mi.	Cm.	Cm.	Cm.	Com.	Cm.	Cm.
1																				
2																				
3																				
4																				
5																				
6																				
7																				
8																				
9																				
10																				
Dec. mean	a	a					a								a	T	a	a	T	a
11																				
12																				
13																				
14																				
15																				
16																				
17																				
18																				
19																				
20																				
Dec. mean	a	a					a								a	T	a	a	T	a

21																				
22																				
23																				
24																				
25																				
26																				
27																				
28																				
29																				
30																				
31																				
Dec. mean	a	a					a								a	T	a	a	T	a
Sum. month.	a	a					a								a		a	a		a
Mean month.	a	a					a								a		a	a		a

---

[1] This must be the difference between the current and succeeding dial readings.

[2] Day movement to cover period 6 a. m. to 6 p. m., unless otherwise specified. Entries to be in total miles for period.

[3] Time of observation is assumed to be the same as for dial readings of anemometer unless otherwise specified.

T—Give total, not average. a, no data required.

For all stations the dial reading should be recorded in the field at each observation, and the dial readings and total movements should be tabulated in adjacent columns of the "Humidity, Wind, and Evaporation" form. The decade means or sums and the monthly sums and means should be computed and entered. For most uses the decade sums will be preferable to means. The record of day and night movements may be obtained either from two dial readings per day, or from hourly automatic records.

Where hourly records are available, the greatest wind movement for any single hour of each day should be entered, and also the total wind movement by day and by night; that is, from 6 a. m. to 6 p. m., and from 6 p. m. to 6 a. m. This division of the daily movement is of interest in the general study of the climate, and may assist, for example, in determining relative amounts of evaporation during the day and night, when this is not readily determined directly.

The monthly, annual, and growing season means of the movements obtained from dial readings, and of maximum hourly velocities, and the sums of day and night movements obtained from automatic records, with the mean hourly movements computed therefrom, may be tabulated on the "Summary" form.

Instruments.

Self-registering Instruments:	
Single register complete (for wind velocity), with a year's supply blank Forms 1015, pen and ink (by special arrangement a register to carry wind record for one week may be obtained)	$95.00
Two magnet registers—	
No. 2, for wind velocity and sunshine (using Form No. 1015–C)	125.00
No. 3, for wind velocity and rainfall (using Form No. 1015–D)	130.00
No. 4, for wind velocity, rainfall, and sunshine (using Form No. 1015–E)	140.00
Quadruple register complete (for wind direction, wind velocity, rainfall, and sunshine), with a year's supply of blank Forms 1017, pens and ink	275.00
In all of the above, cable and battery for electrical installation are extra.	
Anemometers, wind vanes, and supports:	
Anemometer, Robinson's; of the standard pattern, complete with aluminum cups and wrench; all dimensions and construction to be identical and small parts interchangeable with corresponding parts of the anemometer of the Weather Bureau	52.00
Anemometer cups, aluminum, with arms, G. S. S. No. 12200; per set	8.00
Anemometer cups, copper, reinforced, .013 inch thick, hemmed at edges and arms reinforced, G. S. S. No. 12201; per set	9.50
Wind vane; small, for towers, with mounting, complete, G. S. S. No. 12274	13.50

Anemometers, wind vanes, and supports—Continued.

Combined wind vane and anemometer support, 20 feet high, adapted for use with quadruple register; complete with 6-foot vane, electrical contacts, etc., but without anemometer	$105.50
Wind vane, 4 feet, on 7-foot support, with direction arms, gilt letters, and anemometer support, but without anemometer	35.00
Wind vane and support, as above, but without anemometer or anemometer support arm	27.50
Support for anemometer alone, without vane, direction arms, or anemometer	15.00

EVAPORATION.

No ecological study can be considered comprehensive which does not take into account the desiccating power or "evaporation stress" of the atmosphere. While the water supply of the soil has been considered as the condition most directly determining the character of vegetation on a given site, and its rate of growth, almost equal attention must be given to the matter of the dissemination through transpiration of the moisture which reaches the plant. The evaporation rate in different habitats will perhaps be found to show greater variation than any other condition. It is especially valuable, when measured directly, because it gives the integrated effect of wind, humidity, air temperature and sunshine—an integration which can not be accomplished by any artificial means. While it is not to be expected that any instrument will integrate the effect of these different stimuli to evaporation in a manner corresponding to their combined effect on the plant, yet this is the object to which the greatest efforts have been bent and which has to some extent been attained.

The study of the evaporation factor may be made directly, of course, by observing the transpiration of plants in the field. While very desirable and not very difficult, this is perhaps less satisfactory than the instrumental method in reducing the conditions of the environment to physical terms. Since this discussion is mainly concerned with instrumental procedure in forest investigations, the instrumental method, even though less desirable than direct measurements of transpiration, will be considered first.

OBJECTS AND NATURE OF EVAPORATION MEASUREMENTS.

There may be two rather distinct objects in measuring evaporation rates, although in ecology there is only one. Climatologists, irrigation engineers, etc., may desire to know, for local conditions and for general comparative purposes, how much capacity the atmosphere possesses day by day and year by year to take up moisture when offered moisture, as freely as possible, from the surface of a body of water. Obviously this does not measure the capacity of the atmosphere, which could better be determined by humidity observations. For crude comparative purposes, however, the loss from a pan of water is probably as good a measure as any, of general, regional, atmospheric conditions, such as would affect lakes and reservoirs, provided only a standard exposure is employed.

In plant ecology evaporation rates are measured for the purpose of determining how great or how little evaporation tendency, or stress, the plant has to withstand and can withstand without injury. As has been pointed out by Bates (151) under any circumstances the components of evaporation are (1) the heat necessary to transform water into vapor, and (2) the diffusion possibilities of the vapor. In ordinary evaporation there are two possible sources of heat; namely, sunlight, or radiation from any other source, and the heat of the air coming in contact with the evaporating body. By diffusion possibilities are meant the net opportunities for the vapor to move away from the evaporating body. These depend on mechanical obstructions, on the number of vapor molecules already in the atmosphere, on the air movement near the evaporting body affecting this number, but most of all on the temperature, energy, and pressure of the molecules which are moving away. Hence sunlight and almost every atmospheric condition affect evaporation, and it is also plainly evident that each of these factors can not have an identical effect on each of several different evaporating bodies. To use an extreme example, a highly polished metal vessel containing water might be set in full sunlight, and yet the evaporation of the water would not be appreciably influenced by the sunlight, because the heat of the sun would not reach it—the rays would be almost totally reflected. Similarly, the evaporating body may be very largely protected from wind, so far as the wind might affect diffusion. This is to some extent the case in the leaf, where the vapor is largely formed internally.

When, therefore, it is said that in ecology an atmometer is desired which will react to the same external stimuli as affect the plant leaf most directly, it is not by any means implied that the instrument would parallel the plants' transpiration under all circumstances. There should be a certain similarity in their reactions when both are reacting freely. It is not desirable to compare an instrument which is mainly susceptible to wind with a plant which responds in the largest measure to sunlight. If there could be an atmometer which would receive its stimulus from sunlight, wind, air temperature, and humidity in about the same proportions as these four factors affect the plant, the evaporation factor of the habitat could be measured in an effective way. Otherwise, altogether too much emphasis may be placed on some one component, such as wind. After all is said this is almost exactly the same problem as attempting to integrate mathematically the effects of the several components on the evaporation from the plant. One is just as far from an absolutely precise outcome as the other. The advantage of the atmometer is that, once the integration has been accomplished in the construction of the instrument, the observations are relatively simple and no further complex calculations are necessary.

As has been suggested, it is not to be presumed that the atmometer will show restricted evaporation due to control, as may be the case with the plant when it closes its stomata or when transpiration is automatically reduced by increasing density of the cell sap. By comparing the most perfect atmometer with plants, however, it should be possible to measure the actual effectiveness of these plant controls.

It may be worth while to suggest, for the sake of more effective evaporation studies, that it is possibly erroneous for the student of plant life to look upon a large evaporation factor in the habitat as necessarily inimical to the plants which are there. Some theoretical considerations which point to transpiration as a benefit have already been outlined. No attempt will be made, however, to decide the question as to whether it is beneficial to the plant or merely a necessary evil. Laying this question aside, it is perfectly evident that conditions conducive to high transpiration rates are an unavoidable concomitant of the conditions necessary to active photo-synthesis.

When therefore, as in Weaver's (169) succession from prairie to brush or woodland types, it is found that succession produces a steadily decreasing evaporation rate, shall it be concluded that the plants of the brush stage are directly favored by the decreased evaporation, only relatively favored, or not helped at all, but merely able to succeed with less sunlight than the plants of the prairie? Very likely, in a case of this kind, the rate of evaporation, while a serviceable index to the general conditions, may not itself be a controlling factor, or may be a controlling factor only for a brief period in each season when drought occurs. It would appear to be all-important that evaporation rates be closely correlated with the moisture of the soil, as is done by Shreve (166) in giving directly, if somewhat crudely, the ratio of evaporation to soil moisture contents in various habitats. What is perhaps more important is that a clear distinction should be made between evaporation stresses when there is an abundance of soil moisture, and those existing when the moisture supply is nearly exhausted. There are, also, critical periods brought about by excessive evaporation when the soil moisture is apparently all that it should be. These and their effects must be separately analyzed.

The main object of this discussion is to make clear the need for evaporation records day by day, and for a finer analysis of the seasonal records than has been the custom in recent ecological studies.

INSTRUMENTAL METHODS.

The instrumental methods of measuring evaporation may be of two kinds, employing respectively free-water bodies, as in the open tank, and evaporating surfaces which are kept continually moist but in which the water is retained and to some extent withheld from evaporation by capillary action. The latter, for brevity's sake, will be spoken of as nonfree-water methods and instruments. The literature of instrumental evaporation studies is very extensive and has been fully annotated by G. Livingston(162). This discussion must be confined to a few of the more recent efforts.

FREE-WATER SURFACE.

The free-water surface receptacle is used almost exclusively in broad climatological and irrigation studies and only to a limited extent by ecologists. The Weather Bureau has now adopted a standard free-water surface evaporting pan, 10 inches deep, 48 inches in diameter, and constructed of 22-gauge galvanized iron, which is described by Kadel(155). Largely through the work of Bigelow(152), it was determined to be essential, that the receptacle have a surface of known area, that the water exposed in the pan or tank have a known volume, that the surface of the water have a known and as nearly constant distance below the margin of the vessel as possible, and that the material and shape of the receptacle be the same in all cases. All of these conditions are principally effective on the temperature attained by the water, and variation in any one of them is apt to affect the evaporation. The size of the vessel and the water it contains, for example, have much to do with the hourly rate of evaporation. A small vessel of a given aerial surface and depth will give a higher evaporation than will a vessel five times as large, since the water in the smaller vessel will more readily adjust itself to conditions of the surrounding air than the water in the larger pan. The temperature of the evaporating medium, of course, is of great importance in determining the rate at which vapor rises from a pure liquid. It is now the standard procedure to select a very open site for evaporation measurements, avoiding objects which might shade the pan or give it reflected light. The pan is placed on a low platform or crib, only a few inches above the ground, yet allowing air circulation all around it.

Measurements.

The amount of water evaporated is determined by the use of a hook gauge, the loss in any 24-hour period being corrected for precipitation, in accordance with the measurement in a standard rain gauge nearby. The evaporating pan is filled to a depth of 8 inches at the outset, and refilled to this amount whenever the water has receded an inch. The water is occasionally freshened by a complete change.

NONFREE WATER SURFACE.

There are three instruments which have been sufficiently used in this country in recent years to warrant discussion. Each of these three exemplifies a different technical idea.

Piche evaporimeter.

The Piche evaporimeter, as modified by the Weather Bureau, was used considerably 10 years ago and has been described by Russell (164). It consists of a graduated glass tube as a reservoir for the water and a filter paper held over the open end of this tube by means of a horizontal glass plate, a spring, and a pressure screw. It is commonly equipped with a 10-centimeter (4-inch) glass plate and a 9-centimeter filter paper under ordinary conditions, or a 5½-centimeter paper of the same make when evaporation is likely, between observations, to exceed the capacity of the tube, about 40 cubic centimeters. The larger paper exposes 60.91 square centimeters and the smaller 21.06 centimeters. Therefore, quantities evaporated from the smaller papers should be multiplied by 2.891 to make them approximately comparable with the others.

Distilled water should be used in evaporimeters, both because of the effect of soluble substances and to keep the instruments clean and free acting. A nonfreezing solution of 25 per cent denatured alcohol and 75 per cent distilled water has sometimes been used in cold weather; but the value of records obtained under such conditions is questionable, because at times the evaporation is almost wholly from the alcohol, and the ratio between alcohol and water or ice would, of course, depend very largely on the temperature. For this reason the instrument can not properly be considered for freezing weather.

The regulation of pressure on the glass plate is a somewhat complicating and bothersome factor. In dry weather the pressure must be made light to feed the paper sufficiently, and in damp weather it must be quite firm to prevent overflowing on to the glass, if not actual dripping.

Evaporimeters of this kind may best be suspended on wires, having hooks at their lower ends, so that the instruments may be readily taken down for filling. In filling, a long 50-cubic centimeter pipette is found most convenient, making it possible to keep the outside of the tube dry. Care should be taken to have the filter paper wetted and adhering closely to the glass before the instrument is read and left.

It is unnecessary to calibrate these instruments, because of the frequent changing of the filter papers and the fact that papers of one grade may be quite uniform in their capillary properties. Beyond this, the evaporation rate is somewhat controlled by the adjustment and the degree to which the paper is wetted.

The Piche evaporimeter is not now considered so desirable an instrument as some of the other types. Though it is simple and fairly easy to operate under most circumstances, it is fragile and hardly suited to severe weather conditions; the adjustment of the feeding for changes in the weather is always vexatious and sometimes beyond one's power; a correction for rainfall is out of the question; and the technical point may be raised that the moist surface is somewhat too freely exposed to wind, while the white filter paper absorbs only a small proportion of incident radiation. The conditions for evaporation are therefore very different from those within the leaf.

Porous-cup atmometer.

The name "atmometer," while describing any instrument for the measurement of evaporation from a moist surface, is usually associated with evaporimeters of the porous cup type. A very satisfactory field instrument of this type has been described in several papers by Livingston (159), and may be obtained on the market either with or without standardization. Only standardized instruments should be used in comparative studies. The instrument consists of a closed cup with porous walls, into which the water is fed at any desired pressure by regulating the height of the reservoir. The reservoir, connected with the cup by rubber tubing, may be a flask of any size or a graduated tube. In the former case, the amount of evaporation in any specified period may not be determined directly, but rather by measuring the amount of water required to fill the flask to its original level. This feature is inconvenient, but the use of a large flask so increases the possibilities of the instrument for long-period observations that it is, in this respect, far superior to the Piche evaporimeter.

The moisture of the cup reaches the outer surface through the porous walls, its rate of movement being determined by the internal pressure and also by the difference in capillary tension caused by the loss at the outer ends of the pores. Presumably capillary movement is sufficiently rapid to maintain the supply at the outer surface at any reasonable rate of evaporation. Yet there must be a limit to this capillary action in both directions, and for this reason the movement must, under extreme conditions, be governed somewhat according to atmospheric conditions by regulating the hydrostatic pressure. With the outside walls of the cup always moist and yet not dripping, the rate of evaporation will of course be governed by atmospheric conditions. It must not be expected, however, that the evaporation from this instrument may be compared under a variety of conditions with that from the Piche instrument, or with that from a free-water surface. While the absorption of heat from radiant sources and conduction from the air will be practically the same for the water surfaces in the three cases mentioned, yet the further absorption beyond the first water surface will depend on the nature of the substance behind that water surface—in the one case, water; in the second, paper and glass; in the third, clay or some similar earthy substance. Therefore, the three instruments will respond quite differently to the stimuli of warm air and sunshine.

For these reasons, comparative data will be of value only when the same instrument is used in all measurements of the comparison.

Shive's nonabsorbent porous cup atmometer.

It has been the experience of various investigators that the Livingston porous cup atmometer measures the evaporating power of the air with a very considerable degree of accuracy during periods when the temperature is not recorded at or below zero centrigrade.

In 1910, Livingston (158) described a rain-correcting atmometer. This atmometer, while giving great satisfaction in the hands of many inexperienced workers, was difficult to operate in some localities. Thus it was found impossible to obtain continuous records in the dry climate of the Wasatch Mountains of the Manti National Forest in central Utah, principally on account of the connections and joints of the equipment, all of which occurred outside of the water reservoir. Hail storms and objects carried by strong wind were often so severe as to disjoint or break the more delicate equipment. In connection with this instrument, it is understood that the automatic mercury valves which operate to prevent the water absorbed by the porous cup in times of rain from entering the reservoir are externally situated. This makes it essential to have all valves very tightly connected in order to prevent leakage. Much to the satisfaction of those who have used this instrument, Shive (165) has described one so modified as to be self-contained, and at the same time to reduce to the minimum the liability of breakage and the difficulty of adjustment. This was accomplished by eliminating jointed mercury valves and decreasing the leakability and breakage to a nominal degree. The arrangement of the different parts of the instrument is shown in the following detailed diagram (fig. 4). The description of the self-contained instrument, which is particularly adapted to general field work, is quoted from that prepared by Shive.

> From the reservoir (F) two glass tubes (A and B) extend upward through a paraffined cork stopper, and then through a two-perforated rubber stopper into the porous cup, one passing to the tip of the cup, the other just to the upper surface of the rubber stopper. These tubes are of small bore, about 0.8 millimeter inside diameter. Each is bent into a U and continued upward as A′ and B′. One (A′) extends through the paraffined cork (B′) extends upward 6 centimeters to 8 centimeters and is stopper and ends about 5 centimeters above it. The other again bent near the bottom of the reservoir. The tube B is expanded into a small bulb C at its lower extremity, and the tube A′ is expanded into a similar bulb 1 centimeter to 2 centimeters from its lower end. The tube E is about 1.2 centimeters in diameter, and forms a shallow, inverted funnel with the lower surface of the paraffined cork stopper. This serves to conduct air bubbles, which may catch on the undersurface of the stopper in filling the reservoir, to the exterior. The tube extends 5 centimeters above the cork stopper and is graduated to tenths of cubic centimeters. The zero point on the tube serves as a zero point in filling the reservoir.

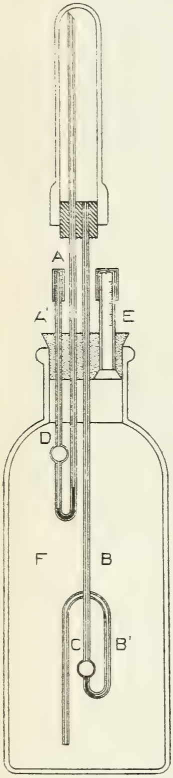

FIG. 4.—Shive's nonabsorbent porous cup atmometer.

> To install the instrument the paraffined cork stopper, into which the tubes A A′, B, and E have been properly fitted, is tightly pressed into the mouth of the reservoir F. A sufficient amount of clean mercury is allowed to fall from a pipette into the openings in the upper end of each of the tubes A′ and B to form a column 5 centimeters to 6 centimeters high in tube A′, and slightly more than this in tube B. After the porous cup has been placed in position and the reservoir filled with distilled water, a rubber tube is attached to the free end of the filling tube A′, and gentle suction is applied. Water rises from the reservoir into the tube B′, at the same time that the mercury in this tube is drawn into the bulb C, where water passes freely and rises in the tube B, filling the porous cup. When the cup is filled, water passes into the tube A A′, the mercury in this tube having been drawn into the bulb D, where the water is allowed to pass freely and escape into the rubber tube, which is then removed. The mercury in the bulbs C and D drops back into the tubes below. To prevent water loss from the reservoir by evaporation through the tube E and to prevent the entrance of water through this tube from without in times of rain, a vial is placed over the end of this tube. A suitable vial is also placed over the end of the tube A′ to exclude dirt. The instrument is now ready for operation.

> To replace the cup with a new one, it is only necessary to remove the old cup from its support and to place the new cup into position, after which suction is applied to the tube A′, as in installing.

> As water evaporates from the surface of the cup, the mercury rises in tube A and falls in tube A′, coming to rest with the mercury level in A, slightly

higher than in A′, the difference in the height of the two columns depending upon the height of the cup above the water level in the reservoir. The mercury in B B′ is drawn into the bulb C, where water rising from the reservoir is freely allowed to pass, supplying in the usual way the water lost from the surface of the cup. The mercury columns in the tube A A′ and B B′ remain in equilibrium in the position indicated in the figure, so long as the water loss from the surface of the cup by evaporation equals or exceeds the absorption from without by any part of its surface. In times of rain, when the water loss from the surface of the cup by evaporation is less than the absorption from without, the automatic mercury valves become reversed. The mercury column falls in A and rises in A′ at the same time that the mercury in bulb C drops into the tube below and rises in the tube B′ (the height to which the mercury rises in this tube depending upon the height of the cup above the water level in the reservoir), thus effectually preventing water from entering the reservoir from this direction. The readings obtained give the actual evaporation minus the error introduced by the volume change required for the operation of the mercury valves, the value of the error thus introduced depending upon the number of complete reversals of the valves.

Standardization.

The Livingston porous-cup atmometers, whether to be used with or without the Shive nonabsorbing apparatus, should be obtained in the standardized form, which insures comparability of the results obtained with different instruments and by different investigators. This standardization of the instruments is one of the strongest features, making it possible, for the first time, for different investigators to speak of evaporation in common terms. Since the standardizing can not be readily accomplished in the field, it is sufficient to state that it is very carefully done at the Johns Hopkins laboratory, where each new instrument is compared with one or more tried instruments. Assuming the rate of evaporation for a certain time to be 100 in a standard instrument, the coefficient of an instrument which in the same period evaporated 150 units, would be 0.67. In short, the coefficient given, for any instrument which has been "standardized," is the amount by which all records of that instrument should be multiplied, to reduce them to a standard basis.

Computation of field results.

In computing the field results to a standard basis, all cups used for a few days or weeks are restandardized. Provided the new evaporating coefficient is found to differ from the original, the probable average coefficient during regular cycles or periods is calculated. It has been shown experimentally that the change in the evaporation coefficient takes place gradually and uniformly during the period of operation (159). Thus, assume that a given atmometer cup having an initial coefficient of 0.62 was exposed in a habitat for a period of four weeks during which it was read three times; namely, at the end of the first, the second, and the fourth week. Upon standardization after the last reading (that is, after the end of the fourth week), the cup, suppose, had a coefficient of 0.70 in place of the original coefficient of 0.62. A variation of 0.08 is therefore to be distributed uniformly over the four-week period. At the end of the first week the assumed coefficient is 0.62; at the end of the second week it is 0.66; and at the end of the fourth week, 0.70. According to the above assumption, the average coefficient for the first week would be 0.63; for the second week, 0.65, etc. Assuming, then, that the reading at the end of the first period—that is, at the end of a week—was 500 cubic centimeters, by reducing to standard units we have the standard reading $\frac{500 \times 63}{100} = 315$ c. c.

Exposure.

This instrument will operate over a long period, the time depending upon the size of the reservoir and the exposure to the evaporating power of the air. For this reason the instrument may be exposed upon remote habitats where weekly, bimonthly, or even monthly readings may be made. Records of this kind, of course, are less conclusive than those made at more frequent periods, but nevertheless have a high value for comparative consideration. Readings taken only bimonthly or so are accurate because of the permanent, rain-correcting adjustment of the instrument, a point which has already been brought out in detail.

Since the instrument is compact and light in weight, it is possible to make the exposure practically wherever desired. If, for example, the investigator desires to determine the evaporation rate near the surface of the ground amidst low-growing, herbaceous vegetation or arborescent seedlings, the reservoir is sunk in the soil so that the avaporating surface of the atmometer is exposed at the height desired. In cases where the evaporation rate is desired at various heights, the instruments may be placed at definite vertical elevations on light supports running out horizontally from a common vertical beam.

The principal disadvantages mentioned with respect to the Piche evaporimeter have been eliminated in the construction of the porous cup with its nonabsorbing attachments. It is of simple construction, not extremely expensive, occupies a small space, and may be equipped with a reservoir which will keep it in operation for an indefinite period. Wind does not disturb it, and small animals and insects have no effect upon its operation. The disadvantages are that the bottle, connecting tubes, and especially the delicate nonabsorbing apparatus are rather easily broken by inexperienced hands, or by roving animals such as domestic stock and deer. A still more serious difficulty is the sensitiveness of the instrument to frost; the slightest freezing of the water in the connecting tubes drives the mercury out of the valves and generally bursts the tubes, which are the most expensive part of the instrument. Even when the air temperature is not below 32° F., but the wet-bulb temperature is below freezing, ice accumulates on the cup in large quantities. In short, the instrument is worthless when the temperatures approach freezing.

Other disadvantages are the necessity for frequent restandardizing, and the occasional failure of the cup to draw moisture from the resorvoir as fast as evaporated. This permits the entry of air, and reduces the evaporating surface, entirely vitiating the results until the cup is refilled.

Forest Service evaporimeter.

To fill the need, in forest studies, for a substantial, essentially indestructible evaporimeter, operating as well in winter as in summer (since it can not be conceded that biological activity ceases with the first occurrence of frost), Bates (151) has designed a metallic, "inner cell" evaporimeter. In addition to these desired practical qualities, it was conceived that an evaporimeter might more closely resemble the leaf, and thereby might show a closer correlation with plant transpiration, by having the evaporating body somewhat protected from air currents. Evaporation takes place in the leaf, not largely on its surface; and, while transpiration is accelerated by wind movement, the latter can not have the direct action upon the water in the leaf and its formation into vapor that it has upon a fully exposed surface.

The correctness of this principle has been demonstrated by comparative tests of evaporation and transpiration under a variety of conditions. The evaporimeter may be briefly described as follows:

The tank or reservoir has a capacity of about 450 cubic centimeters, sufficient for a week's operation under extreme conditions. It is seamless and is not ordinarily injured by freezing. It is protected by an outer shell of polished metal, which insulates it both against temperature changes and against direct radiation.

Out of the tank rises a stem a few inches long and one-half inch in diameter, carrying the feed-wick, which is a piece of linen rolled into cylindrical form with the threads "drawn" at one end. At the top of the stem this wick is flattened out to make a contact with the evaporating wick. The evaporating wick is a flat, circular piece of linen having an area of 100 square centimeters. It rests upon a perforated metal disk of the same size, the perforations aggregating an area of 5 square centimeters, and designed to simulate the stomata of the under side of a leaf. All vapor formed must escape through these perforations. The disk is firmly attached to, and flush with, the upper end of the stem.

Over the wick is a cover only slightly larger than the disk, whose flanged edge extends down over the edge of the disk. This is held down by two screws, which engage the flanged edge. The cover is flat, but seamless, and completely excludes rain or snow. Its surface is finished with nickel and an instrument having this polished surface absorbs practically no radiant energy and is called a "shade" instrument. To obtain the effects of radiation, an instrument whose cover has been coated dead-black is used. The "shade" instrument is now entirely abandoned, since it has been seen that the difference between the two is not a measure of sunlight intensity, but a measure of the addditional effect of sunlight in producing evaporation. This effect can not under any circumstances be ignored in ecological studies.

The tests which have been made show that the losses from the blackened instrument of this type follow more closely those from potted trees, under a great variety of atmospheric and solar conditions, than do the losses from any other type of instrument at present available. The instrument has also shown itself remarkably free from annoying characters, and responsive to all degrees of evaporation stress. It may be considered, however, something of a disadvantage that the amount evaporated is relatively small. The losses for short periods may, therefore, only be determined by very precise weighing.

OBSERVATIONS.

With the Forest Service evaporimeter the daily observations consist in weighing the instrument, usually on an inexpensive balance such as the Harvard trip scale. Refilling is undertaken as often as necessary to maintain between 100 and 200 cubic centimeters of water in the tank. The "closing" weight and "refilled" weight are entered on the field observation form, together with the number of the instrument. Computations of losses are usually made when entering the data on Form 8, and the correction in accordance with the calibration of the instrument is usually applied only to the total losses for 10-day periods.

With porous cups the daily or periodic observations will usually consist in an entry of the amount of water required to fill the reservoir to datum level. A graduate is taken into the field to measure this amount.

In the case of the Piche evaporimeter, losses are calculated from the readings of the graduated reservoir. Note should always be made of observed overflowing or drying-up of the filter paper or evaporating surface, and the probable correction due to these failures of the instrument should in all cases be estimated and entered in the "Corrections" column of the field form "Daily Observations." Interpolations of this character should be indicated by asterisks on the "Humidity, Wind, and Evaporation" form.

TABULATION.

The tabulation of evaporation data on the "Humidity, Wind, and Evaporation" form consists in setting down all of the recorded weights of the evaporimeters, or graduate readings, and the losses computed therefrom. In the record for porous cup atmometers, there will usually be but one entry for each observation, though these instruments may also be handled on a weight basis more satisfactorily than on a volume basis. The corrections for calibration are made usually on the sums for 10-day periods.

Form Z

Daily observation at ....

Date or station No.					
Time					
Datum:					
Maximum temperature, air					
Minimum temperature, air					
Current temperature, air					
Current thermograph pen					
Psycrometer:					
Dry bulb					
Wet bulb					
Anemometer dial					
Soil temperature:					
Surface					
1 foot					
2 or 4 feet					
Curr. thermograph					
Evaporimeter—Number:					
Closing reading					
Refilled to					
Amount since last ob					
Evaporimeter—Number:					
Closing reading					
Refilled to					
Amount since last ob					
Current precipitation:					
Water, inches					
Snow, inches					
Snow on the ground, inches					
Frost (indicate by X or XX)					
Barometer, inches					
Phenology:					
Tree 1					
Tree 2					
Tree 3					

Date or month ....

Initials of observer ....

The annual summary of evaporation should be made on the "Summary" form and should consider the total evaporation by decades, months, the year, and the growing season. It may also be desirable to record the maximum rate noted during each month or decade.

DIRECT TRANSPIRATION METHODS.

In evaporation studies connected with plant life the chief purpose is to obtain in as simple a term as possible a measure of the habitat conditions, as they may affect transpiration. The response of the plant to these conditions will be governed by physical facts that can be fairly well comprehended, and by biological conditions which are still more or less obscure. While, then, transpiration studies may be made in lieu of evaporation studies, it will be far more profitable to consider the one as supplementing the other, giving an insight into plant functioning which can only be obtained as observations are reduced to terms of well-known physical laws. One of the means of determining the intensity or transpiration is by the aid of cobalt chloride paper.

Cobalt-chloride method.

Although the actual amount of water transpired by a plant can not be ascertained by means of the standardized cobalt-chloride paper. this method is particularly adapted to field use where merely relative rates of transpiration are desired, and for showing variations in rate with changes in environmental conditions. It is hardly necessary to point out that it would be almost impossible to apply to needle leaves. The method depends upon the fact that paper impregnated with a weak solution of cobalt chloride is blue when dry, but when exposed to moisture gradually turns pink. Specially prepared "tripartite cobalt-chloride paper slips" may be purchased. These slips are made up of three small strips of paper— a deep blue standard, a light blue standard, and between them a strip of cobalt chloride paper. In practice the strip is heated over a small flame or heated surface until the cobalt chloride strip is of a more intense blue than either standard. It is then applied to the surface of the leaf under consideration and held by small glass clips. When the cobalt chloride strip fades so that it matches the bluest standard, the time is noted. When it fades further and matches the light blue standard, the time is again noted and the elapsed time is recorded. This process should be repeated several times to assure a good average. A thermometer should also be hung amidst the foliage to give the temperature of the leaves.

The time taken for the cobalt-chloride paper to make the change in color between the two standards is the measure of the rate of transpiration of the leaf. In order to refer this to a definite standard, it is compared with the time required by the strip to make the same change over a free-water surface blanketed by one millimeter of air at a temperature the same as the leaf. The reaction time of each slip must therefore be ascertained under standard conditions. The apparatus for making these standardizations is described in detail by Livingston and Shreve (161).

It would obviously be a great labor to determine the reaction time of each slip for every temperature likely to be used; but this is unnecessary, because if the time is determined for one temperature it can be easily derived for any other, since it is inversely proportional to the pressures of saturated aqueous vapor at the different temperatures.

The chief objection to the method is the large personal equation involved. The fading of the slip is very slow indeed, and no perceptible change may occur for many seconds. Practically the system seems to work out well and yields much more consistent results than potometers. It is easily used in the field and in all kinds of sites, and appears to be a valuable addition to field research methods.

Method of excised twigs.

In measuring transpiration by means of cut twigs placed in potometers, the actual amount of water given off per unit of leaf surface can be determined.

The apparatus used consists of a flask closed with a two-hole rubber stopper, in one hole of which is inserted a glass tube bent at right angles: in the other the twig is sealed. The horizontal section of the glass tube is graduated so that it may be used to measure the water removed by the twig, and is drawn to a fine point at the end to minimize evaporation from the end of the tube. The twigs must be cut off under water and the ends must be kept continuously wet, or large variations in transpiration will occur. The sealing into the potometers must be very carefully done also, as the least leak will totally vitiate results. This method is particularly useful when it is desirable to determine transpiration of several species or in several sites simultaneously. The results tend to be erratic, however, and accordingly the determinations should be made in duplicate, at least to avoid gross errors. The same twigs can only be used for a short time, after which fresh ones must be obtained.

To determine the leaf area, as must be done to reduce the transpiration to amount per unit surface, the simplest method is to cut a number of pieces of known area with a cork cutter, or preferably a centimeter punch, weigh them, and then weigh the residue of the leaves and figure their area proportionately.

Method of potted plants.

The method of determining the transpiration rate, either in the laboratory or under a variety of field conditions, by means of potted plants, is theoretically the most reliable, since, if the potted plants are kept in a healthy condition and the moisture supply in the soil is properly regulated, a very near approach to natural growth conditions may be obtained. Unquestionably, the rate of transpiration is limited by the moisture supply. Where tests of this character are made in the field the moisture content of the pots may at all times be similar to that of the native soil at the point studied, allowance being made, of course, for differences in physical properties of the two soils, if any exist. A much simpler method is to maintain the pots constantly at a standard moisture content known to be near the optimum. Thom and Holtz (168) and Kiesselbach (156) have shown that the maximum transpiration occurs when the soil is about half saturated. This may be the result of aeration, or it may be that "about half saturation" corresponds to the "critical moisture content" of Cameron and Gallagher (117), in which case it is more likely to be a question of osmosis.

A method of treating plants that seems especially adapted to good-sized trees is that of Briggs and Shantz (153, 154), having been employed to determine the amount of water used by various agricultural crop plants under semiarid conditions at Akron, Colo. These tests were made on a large scale, with all arrangements designed for outdoor exposure. The pots were galvanized ash cans, through the covers of which the stems of the plants were made to extend after growth had become well established. The weighing of such pots was laborious, of course, and required the use of a traveling crane arrangement, by means of which the cans were lifted to the scales for each weighing. A very similar arrangement would appear practicable for determining transpiration from tree specimens, until they had attained the height of at least 4 or 5 feet.

For the convenient handling of forest tree seedlings up to 5 or 6 years of age, a galvanized iron can, 4 inches in diameter and 10 inches deep, has been used by Bates (105). This can is soldered and there are no perforations in the bottom through which water can escape. Before the seedlings are potted, a 2-inch clay flowerpot is inverted in the bottom of each can. Through the hole in the base of the flowerpot a glass tube of small bore, bent with two right angles so that the main part of the tube rests against the wall of the galvanized can, is inserted. It extends slightly above the wall of the can. This glass tube serves to feed water into the porous pot, whence it is readily diffused through the soil, and at the same time permits the entrance of air, which may be obtained by the roots through the walls of the pot, insuring their maintenance in a healthy condition.

For the best distribution of moisture in the soil, it is desirable that a second tube, or a tee connection on the longer one, should be placed so as to extend about an inch below the soil surface. Since there will be some escape of vapor from each of these tubes, a pot similarly prepared, but containing no tree, should be run as a measure of such loss, under the various conditions to which the trees are exposed.

The weight of the can, pot, and glass tube is first obtained. The seedling to be potted is then weighed with the minimum of exposure to the air. The seedling is then placed in the can, which is filled with moderately dry soil, and the weight of the whole is obtained immediately after potting, following which water may be given to the plant. Having now the weight of the air-dry soil which has been placed in the pot, its net oven-dry weight may readily be computed, after drying small samples of the same soil; and from this net weight may be calculated the amount of water which the pot should contain at all times to maintain a moisture equal to 50 per cent, let us say, of the saturation capacity of the soil. Once the soil is well settled by watering, the top of the can is sealed with a mixture of paraffin and vaseline. A measured amount is used, so that the weight of this substance may also be included in the total weight which the outfit should show at the desired moisture condition.

Knowing the weight which the outfit should have at a certain moisture condition, the simplest method of measuring the transpiration is to put the can on one side of the scales and the desired weights on the other side, and to inject water from a burette until a balance is obtained. The water may alternately be injected through the long and the short glass tubes.

The transpiration results will be most expressive if given in terms of transpiration per unit of leaf area; but since, with coniferous seedlings, the determination of leaf area with any precision is next to impossible, the plan of computing the loss per unit of weight of the plant may be considered.

Where a number of plants, even though of the same species and grown under the same conditions, are to be placed in potometers for transpiration study under a variety of field conditions, the plants should by all means be calibrated under the same conditions before being distributed, since extremely great variations in individuals seem to be inherent.

INSTRUMENTS (APPROXIMATE PRICES).

Piche evaporimeter, modifications used by Weather Bureau; graduated to 0.2 cubic centimeter, capacity about 40 cubic centimeters. Supplied with glass plate 9 centimeters in diameter, and 1 dozen paper disks, No. 345 *b*	$6.50
Paper disks for evaporimeter, per dozen, No. 345 *c*	.25
Livingston porous-cup atmometers:	
Natural cups, cylindrical with smoothly ground surface, for general purposes	.50
Coated cups, glazed at base, with permanent numbering	.60
Spherical cups, standardized	1.00
Shive's nonabsorbing attachment	6.00
Forest Service evaporimeters, equipped with wicks, blackened and calibrated	11.00
Evaporating pans, 10 inches deep, 4 feet in diameter, constructed of No. 22 gauge B. W. G. galvanized iron; can be constructed locally or secured through the United States Weather Bureau.	
Cobalt-chloride paper slips, "tripartite."	
Clips, glass, for attaching cobalt-chloride paper to leaves.	

PHENOLOGY.

The prevailing idea of ecology as a science through which the mysteries of plant and animal life may be solved merely by measuring the environment in more or less exact terms, is gradually giving way to a conception of ecology as a phase of physiology. In the preceding sections it has been attempted to bring out the concept of physiology, at least in its broader aspect, as a basis for those observations and measurements which are commonly associated with ecological studies. Unless the nature of physiological reactions in the plant is understood in a general way, the stimuli which are important to plant life, can not be correctly measured; that is, the environment can not be measured in terms which are expressive. On the other hand, each such effort, by reducing the stimulus to physical terms, permits a little better understanding of the activities of the plant, by placing them more nearly on a physical basis. Thus physiology and ecology must advance side by side, or, to use a crude simile, like the tread on a caterpillar tractor, in which each segment is in turn brought forward to a point where it may perform its temporary function.

Now, in fact, phenology is ecology as applied to functions of plants and animals which are more or less regularly periodic or seasonal in character. Unfortunately, much good effort has been wasted on phenological observations, particularly in connection with trees—wasted, because no correlation was attempted between the phenomena of growth and any other condition except time, calendar dates. Again, effort has been wasted because, while correlation between growth and climatic conditions was attempted, the observations on growth particularly were too crude; no means was at hand of determining closely when growth began, how rapidly it proceeded, when it ceased. In consequence, phenological observations have fallen into disrepute.

The object of these conclusions is to suggest that, after all, in the study of ecology there is nothing more important than the behavior of the plant itself, its reactions at various times and seasons; in other words, phenology in the fullest sense. Otherwise, ecological studies may as well be left to climatologists and soil physicists.

How, then, may observations on the plant be made worth while? The observable external phenomena which accompany a reaction to certain environmental conditions must be measured more precisely than in the past if they are to serve any useful purpose. There is room here for instrumental development, quite as much as in the study of the environment. The field has been even more neglected. Again, there is opportunity for studying changes in the plant through internal physical and chemical conditions. This brings this study directly into the field of physiology, which can not be covered further than has already been done. Finally, experimental physiology, or the study of reactions to a limited change in environment, most of the conditions being stable and under control, is necessarily a laboratory study. The nature of the studies involved has been indicated in preceding discussions, especially in connection with light and soils studies. They may have a very useful result in showing how better to study conditions in the field, but they do not take the place of field observations. The reactions produced by changing one factor while other conditions are more or less perfectly controlled, may not be at all the same as in the field where all the factors vary synchronously. After all, then, the problem for the ecologists simmers down to one of determining plant reaction in the field as closely as possible.

In the past the plant society has perhaps been used too much as an index to reactions: that is, the effect of environmental conditions has been judged almost wholly by end results, in which competition plays an important part. A plant is either absent from a given site, occasional, abundant, moderately successful, or vigorous and dominant. From this is judged the extent to which the species is favored or inhibited by the environmental conditions that have been measured. This method is altogether too gross and undoubtedly has led to a great many erroneous conclusions. A great deal more is to be learned as to the requirements of different species by closer observation of individuals.

EXTERNAL FIELD OBSERVATIONS.

At each station where the environment is being studied, one or more individual trees should be permanently marked and numbered, and their condition should be a matter of daily observation. The number of trees chosen will depend upon the composition of the stand. Where even-aged stands of one species are studied, probably two representative trees of the dominant and codominant classes will be sufficient. In all-aged stands, at least three trees of various ages above reproduction should be included and two sets of such trees if the stand contains more than one prominent species, or if the site is being studied from the standpoint of more than one species. In studies of reproduction conditions, the smallest seedlings available should be under observation.

In these external observations, Forest Service Form 416 may be used as a guide, since it covers comprehensively the ordinary phenological observations. A reduced copy of this form may well be kept in the field notebook, and the field observations may be given in the form of numbers corresponding to the captions of the "Phenological Observations" form. For example, "1" would be used to indicate that buds were beginning to swell.

As has been said, ocular observations on these common phenomena of growth, especially at the actual beginning of tree growth in the spring and its termination in the fall, are too crude. Some method of measuring and recording the actual growth from day to day is required. A number of auxometers might be mentioned, but a meter really adapted to plants in the field, and especially the exposed swaying tops of trees, has not been produced, so far as the writers know. There is unlimited field here for invention.

Form 416.

[U. S. Department of Agriculture, Forest Service.]

PHENOLOGICAL OBSERVATIONS.

Species ______________________________.

Period covered by observations____

Name of observer ____

Residence____

(State.) (County.) (Town.)

General character of country.—*Mountains; foothills; plains; river valley; seacoast.*

Situation of trees.—*Level; slope (north, east, west, south); hilltop; river bottom; soil (sandy, clayey, heavy, light, deep, shallow, moist, dry); forest; open ground; park; street.*

(Please check the words which apply to your particular locality and to the trees observed.)

Approximate elevation above sea level__________________________________

Location of nearest Weather Bureau station_____________________________

State if season was wet or dry, early or late, etc______________________

Date.

1. *Swelling of buds*__________________
2. *Bursting of buds*__________________
3. *Beginning of leafing out*___________
4. *General leafing out*_______________
5. *Beginning of blossoming*___________
6. *General blossoming*________________
7. *Change in color of foliage*_________
8. *Beginning of leaf falling*__________

Date.

9. *End of leaf falling*_______________
10. *Beginning of seed ripening*_______
11. *General seed ripening*____________
12. *Beginning of seed falling*_________
13. *End of seed falling*______________
14. *Quantity of seed*________________
15. *Quality of seed*_________________

General remarks____

____

Instructions on back of this form should be followed strictly.

Under the name "dendograph" McDougal[22] has designed a new instrument for measuring and recording the diameter growth of tree stems. This instrument is being thoroughly tried out. It will probably be a vary valuable adjunct. It is not simple in construction or operation, however, and will always be too expensive to be extensively used. It would seem that a beginning must be made in a more simple way, perhaps through circumferential measurements, even though a number of complicating factors must be taken into account, such as the expansion of the tree and of the tape with increased temperatures.

INTERNAL OR PHYSIOLOGICAL OBSERVATIONS.

Although the forester is prone to think of growth as the major reaction of interest, it is entirely possible that there may be positive gain in studying the more fundamental reactions which lead up to growth. For example, in the conifers, the outward evidences of growth may disappear by midsummer, so far as height accretion is concerned; yet diameter growth continues longer, and this period of relative inactivity is of great importance in accumulating a reserve for the effort of the following season. Is it not logical, therefore, that the growing season for trees should be considered to be the entire period in which materials for growth are being produced?

Again, while growth is a large factor when competition begins, the critical conditions which have the greatest bearing on the success of the individual and species, and thereby affect most acutely the character of the plant formation, may, in the case of all perennial plants, be encountered not in the growing season but in the dead of winter. Through neglect of this period erroneous conclusions may again be reached as to the importance of various conditions in building up the plant formation.

It should therefore be most desirable to be able to determine the physiological conditions of the plant frequently in order that its reaction to every change in environment may be followed. The writers know of no single method or basic method of following these reactions which promises more than the method of following the plant's condition by frequent observations on the osmotic pressure or sap density. In the case of trees, the termini should of course be studied, but it is probable that valuable supplemental data can be obtained at one or two points along the stem and on side branches. Through this method, with any individual tree, it may be possible to depict the sudden influx of sap in the spring, which precedes the first growth; the gradual increase in carbohydrates as the new tissues continue to function, and temporary changes due to water supply and water loss. Possibly the end point of the season's photo-synthetic activity may be found, if there is any; the same method will show the changes which the tree undergoes through the winter. In addition to osmotic pressures, the starch content of leaves should be examined from time to time. It is self-evident that these data can only be interpreted when correlated with observations on both the soil and atmospheric conditions.

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[22] MacDougal, D. T. Growth in Trees. Pub. 307, Carnegie Inst. Washington, 1921.

A method which would show the rate at which the tree is being supplied with water would be a valuable adjunct to the above; but no attempt of this nature is known, beyond transpiration studies. It is possible, however, that a means may be devised by which this rate may be directly determined. There is room for a great deal of development in these lines.

FIELD OBSERVATIONS, PHOTOGRAPHS, AND MAPS.

The "Daily Observations" form in the series for climatological studies, intended for field observations, is thought to be adapted to universal use. It is of a size to fit Forest Service loose-leaf notebooks, 6⅞ by 4 inches. It contains lines for all factors on which regular observations are likely to be taken. It has five vertical columns, which may be used for five stations visited consecutively on the same day, or for a single station visited for five consecutive observations. In the first instance the numbers of the stations would be stamped at the heads of the several columns and the date would be stamped at the bottom. In the second instance the days of the month would be stamped at the heads of the several columns and the month and year at the foot of the form. In either case the exact time of observation should be entered in the second line of each column. Since observations at completely equipped stations may take from 10 to 20 minutes, the time entered for such stations should be, as nearly as possible, the time of reading current temperature and anemometer, these conditions being subject to considerable changes in a few minutes.

Each point chosen as a site for ecological study should, in addition to a complete description[23] of the features which may influence soil quality, insolation, wind exposure, etc., be witnessed by photographs and topographic map. The former should be taken from as many positions as possible to show the general position of the station with respect to topographic features, to show the position of the trees which may influence atmospheric factors, to furnish a map of the canopy (by vertical view) which affects the insolation at the ground, and finally to show in detail the nature of the ground and ground cover. The view of the canopy should be taken as nearly as possible from the position which will be occupied by solar apparatus and evaporimeter.

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[23] The "Description" form is suggestive.

The local topographic map should be made on a scale adequate to show in detail the immediate surroundings and those which are close enough to have appreciable effect on insolation, wind velocity, etc. Especially when two or more stations in close proximity, but different presumably in some essential aspect, are being studied, should the map be made full enough to bring out clearly the contrast which exists in conditions. In such cases a joint map for the several stations may well be used. Such maps should, if possible, be restricted to the size of the tabulating forms used.

Form 1.

[U. S. Forest Service, Physical Survey.]

DESCRIPTION OF OBSERVATION POINT, LIMITED AREA, TREE ENVIRONMENT.

Project ———

Station No-------------------------- Area involved ----------------------
Forest type ------------------------- Absolute elevation--------------------
Permanent sample plot No----------- Block No ---------------------------
National Forest --------------------- Nearest post office------------------
County ----------------------------- State----------------------------------
Legal location----------------------- Exact location ----------------------

TOPOGRAPHIC FEATURES.

Aspect-------------------------------- Gradient-----------------------------
Distance from ridge------------------ Distance from channel---------------
Elevation above water---------------- Wind exposure ----------------------
Air drainage conditions---
Elevation of horizon to east ------; west ------; north ------; south ------
Character of topography---

FOREST ENVIRONMENT.

Distance of nearest trees to north -----; east -----; south -----; west -----
Age of trees-------------------------- Height-------------------------------
Diameter ----------------------------- Trees per acre----------------------
Stand, feet b. m---------------------- Stand, cubic feet--------------------
Growth rate; height, diameter, or cubic feet per A. A----------------------
Shading, amount ---------------------- From trees on------------------------
Light at the ground, per cent-------- Determined by ---------------------

Summary of forest conditions affecting reproduction or the special tree under observation, as to shading, exhaustion of soil moisture, influence of herbaceous vegetation, underbrush, etc______________________________________

____

____

Description of the special tree under observation as to size ,growth, vigor. and reproductive capacity;__________________________ _________________________

____

SOIL CHARACTER AND MOISTURE SUPPLY.

Depth of litter________________________ Character____________________________
Depth of humus______________________ Present moisture _____________________
Penetration of humus in mineral soil as shown by color, inches________________
Character of subsoil, distinguished from soil_______________________________
Total depth of soil permeable to roots, inches_______________________________
Amount and kind of rock fragments in soil___________________________________
Character of impermeable substratum____
Soil origin (in situ, colluvial, alluvial, or eolian, and from what rocks)_______

____

Composition and class____
Drainage _____________________________ Present moisture _____________________

REFERENCES.

Maps____
Reports____
Photographs____
Environmental conditions measured____
Moisture samples______________________ Samples for analysis_________________
Soil analyses filed____
Observations by_____________________(date)_____________________.

APPENDICES.

APPENDIX A.

VAPOR PRESSURE TABLES—WAGON WHEEL GAP, COLORADO.

The accompanying table for obtaining vapor pressures from reading of the dry and wet bulb thermometers was computed by Mr. B. C. Kadel for a pressure of 21.42 inches, from the Ferrel psychrometric formula used by the Weather Bureau:

$$e=e'-0.000367\mathrm{B}\ (t-t')\left(1+\frac{t'-32}{1{,}571}\right)$$

in which t and t' are the temperatures of the dry and wet bulb thermometers in degrees Fahrenheit, B is the barometric pressure in inches, e' is the saturation pressure of aqueous vapor at the temperature t' of the wet bulb, and e is the vapor pressure corresponding to the thermometer readings. The constants of the formula were determined by Profs. Hazen and Marvin, of the United States Weather Bureau.

TABLE 8.—*Values of* $0.000367\ P\left(1+\frac{t'-32}{1{,}571}\right)$ *when* $P=21.42$ *inches, log.* $0.000367\ P=7.89549$.

t'	$1+\frac{t'-32}{1{,}571}$	log.	+7.89549	Product.
−35.....	0.95736	9.98107	7.87656	0.007526
−30.....	.96054	9.98252	7.87801	.007551
−25.....	.96372	9.98395	7.87944	.007576
−20.....	.96690	9.98538	7.88087	.007601
−15.....	.97008	.98681	.88230	.007626
−10.....	.97327	.98824	.88373	.007651
−5......	.97645	.98965	.88514	.007676
Zero.....	.97963	.99106	.88655	.007701
5........	.98282	.99248	.88797	.007726
10.......	.98600	.99388	.88937	.007751
15.......	.98917	.99527	.89076	.007776
20.......	.99236	.99667	.89216	.007801
25.......	.99554	.99806	.89355	.007826
30.......	.99873	.99945	.89494	.007851
35.......	1.00191	.00083	.89632	.007876
40.......	1.00509	.00221	.89770	.007901
45.......	1.00827	.00358	.89907	.007926
50.......	1.01146	.00495	.90044	.007951
55.......	1.01464	.00632	.90181	.007976
60.......	1.01782	.00767	.90316	.008001
65.......	1.02101	.00903	.90452	.008026
70.......	1.02418	.01038	.90587	.008051
75.......	1.02737	.01173	.90722	.008076
80.......	1.03055	.01307	.90856	.008101
85.......	1.03373	.01441	.90990	.008126
90.......	1.03692	.01575	.91124	.008152

TABLE 9.—*Vapor pressure, inches; barometer 21.42 inches; depression of wet bulb (T.—t′), °F.*

WET BULB −16° TO −8°.

Wet bulb.	0.0	1.0	2.0	Wet bulb.	0.0	1.0	2.0	3.0	Proportional parts.	
									Degrees.	*Inches.*
−16.0	0.0159	0.0083	0.0007	−12.0	0.0199	0.0123	0.0046	....	0.1	0.0008
−15.9	.0160	.0084	.0008	−11.9	.0200	.0124	.0047	....	.2	.0015
−15.8	.0160	.0084	.0008	−11.8	.0201	.0125	.0048	....	.3	.0023
−15.7	.0161	.0085	.0009	−11.7	.0202	.0126	.0049	....	.4	.0031
−15.6	.0162	.0086	.0010	−11.6	.0203	.0127	.0050	....	.5	.0038
−15.5	.0163	.0087	.0011	−11.5	.0204	.0128	.0051	....	.6	.0046
−15.4	.0164	.0088	.0011	−11.4	.0206	.0130	.0053	....	.7	.0053
−15.3	.0165	.0089	.0012	−11.3	.0207	.0131	.0054	....	.8	.0061
−15.2	.0166	.0090	.0013	−11.2	.0208	.0132	.0055	....	.9	.0069
−15.1	.0167	.0091	.0014	−11.1	.0209	.0133	.0056	....		
−15.0	.0168	.0092	.0015	−11.0	.0210	.0134	.0057	....		
−14.9	.0169	.0093	.0016	−10.9	.0212	.0136	.0059	....		
−14.8	.0170	.0094	.0017	−10.8	.0213	.0137	.0060	....		
−14.7	.0171	.0095	.0018	−10.7	.0214	.0138	.0061	....		
−14.6	.0172	.0096	.0019	−10.6	.0215	.0139	.0062	....		
−14.5	.0173	.0097	.0020	−10.5	.0216	.0140	.0064	....		
−14.4	.0174	.0098	.0021	−10.4	.0217	.0141	.0065	....		
−14.3	.0175	.0099	.0022	−10.3	.0218	.0142	.0066	....		
−14.2	.0176	.0100	.0023	−10.2	.0220	.0143	.0067	....		
−14.1	.0177	.0101	.0024	−10.1	.0221	.0144	.0068	....		
−14.0	.0178	.0102	.0025	−10.0	.0222	.0145	.0069	....		
−13.9	.0179	.0103	.0026	− 9.9	.0223	.0146	.0070	....		
−13.8	.0180	.0104	.0027	− 9.8	.0224	.0147	.0071	....		
−13.7	.0181	.0105	.0028	− 9.7	.0226	.0149	.0073	....		
−13.6	.0182	.0106	.0029	− 9.6	.0227	.0150	.0074	....		
−13.5	.0183	.0107	.0030	− 9.5	.0228	.0151	.0075	....		
−13.4	.0184	.0108	.0031	− 9.4	.0229	.0152	.0076	....		
−13.3	.0185	.0109	.0032	− 9.3	.0230	.0153	.0077	....		
−13.2	.0186	.0110	.0033	− 9.2	.0232	.0154	.0079	....		
−13.1	.0187	.0111	.0034	− 9.1	.0233	.0155	.0080	....		
−13.0	.0188	.0112	.0035	− 9.0	.0234	.0157	.0081	0.0004		
−12.9	.0189	.0113	.0036	− 8.9	.0236	.0159	.0083	.0006		
−12.8	.0190	.0114	.0037	− 8.8	.0237	.0160	.0084	.0007		
−12.7	.0191	.0115	.0038	− 8.7	.0238	.0161	.0085	.0008		
−12.6	.0192	.0116	.0039	− 8.6	.0239	.0162	.0086	.0009		
−12.5	.0193	.0117	.0040	− 8.5	.0240	.0163	.0087	.0010		
−12.4	.0194	.0118	.0041	− 8.4	.0242	.0165	.0089	.0012		
−12.3	.0195	.0119	.0042	− 8.3	.0243	.0166	.0090	.0013		
−12.2	.0196	.0120	.0043	− 8.2	.0244	.0167	.0091	.0014		
−12.1	.0197	.0121	.0044	− 8.1	.0246	.0169	.0093	.0016		
−12.0	.0199	.0123	.0046	− 8.0	.0247	.0170	.0094	.0017		

WET BULB −8° TO −0°.

Wet bulb.	0.0	1.0	2.0	3.0	Wet bulb.	0.0	1.0	2.0	3.0	4.0
−8.0	0.0247	0.0170	0.0094	0.0017	−4.0	0.0307	0.0230	0.0153	0.0077	0.0000
−7.9	.0248	.0171	.0095	.0018	−3.9	.0309	.0232	.0155	.0079	.0002
−7.8	.0249	.0172	.0096	.0019	−3.8	.0311	.0234	.0157	.0081	.0004
−7.7	.0250	.0173	.0097	.0020	−3.7	.0313	.0236	.0159	.0083	.0006
−7.6	.0252	.0175	.0099	.0022	−3.6	.0315	.0238	.0161	.0084	.0008
−7.5	.0254	.0177	.0101	.0024	−3.5	.0316	.0239	.0162	.0085	.0009
−7.4	.0255	.0178	.0102	.0025	−3.4	.0318	.0241	.0164	.0087	.0011
−7.3	.0256	.0179	.0103	.0026	−3.3	.0320	.0243	.0166	.0089	.0013
−7.2	.0257	.0180	.0104	.0027	−3.2	.0322	.0245	.0168	.0091	.0015
−7.1	.0258	.0181	.0105	.0028	−3.1	.0324	.0247	.0170	.0093	.0017
−7.0	.0260	.0183	.0107	.0030	−3.0	.0325	.0248	.0171	.0094	.0018
−6.9	.0262	.0185	.0109	.0032	−2.9	.0327	.0250	0173	.0096	.0020
−6.8	.0263	0186	.0110	.0033	−2.8	.0329	.0252	.0175	.0098	.0022
−6.7	.0264	.0187	.0111	.0034	−2.7	.0330	.0253	.0176	.0099	.0023
−6.6	.0266	.0189	.0113	.0036	−2.6	.0332	.0255	.0178	.0101	0024
−6.5	.0268	.0191	.0115	.0037	−2.5	.0334	.0257	.0180	.0103	.0026
−6.4	.0269	.0192	.0116	.0038	−2.4	.0336	.0259	.0182	.0105	.0028
−6.3	.0270	.0193	.0117	.0039	−2.3	.0338	.0261	.0184	.0107	.0030
−6.2	.0272	.0195	.0119	.0041	−2.2	.0340	.0263	.0186	.0109	.0032
−6.1	.0274	.0197	.0121	.0043	−2.1	.0342	.0265	.0188	.0111	.0034
−6.0	.0275	.0198	.0122	.0044	−2.0	.0344	.0267	.0190	.0113	.0036

TABLE 9.—*Vapor pressure, inches; barometer 21.42 inches; depression of wet bulb (T.—t′), °F*—Continued.

WET BULB −8° TO −0°—Continued.

Wet bulb.	0.0	1.0	2.0	3.0	Wet bulb.	0.0	1.0	2.0	3.0	4.0
−5.9	.0276	.0199	.0123	.0046	−1.9	.0346	.0269	.0192	.0115	.0038
−5.8	.0278	.0201	.0125	.0048	−1.8	.0347	.0270	.0193	.0116	.0039
−5.7	.0280	.0203	.0126	.0050	−1.7	.0349	.0272	.0195	.0118	.0041
−5.6	.0281	.0204	.0127	.0051	−1.6	.0351	.0274	.0197	.0120	.0043
−5.5	.0282	.0205	.0128	0052	−1 5	.0353	.0276	.0199	.0122	.0045
−5.4	.0284	.0207	.0130	.0054	−1.4	.0355	.0278	.0201	.0124	.0047
−5.3	.0286	.0209	.0132	.0056	−1.3	.0357	.0280	.0203	.0126	.0049
−5.2	.0287	.0211	.0133	.0057	−1.2	.0359	.0282	.0205	.0128	.0051
−5.1	.0289	.0213	.0135	.0059	−1.1	.0361	.0284	.0207	.0130	.0053
−5.0	.0291	.0214	.0137	.0061	−1.0	.0363	.0286	.0209	.0132	.0055
−4.9	.0292	.0215	.0138	.0062	−0.9	.0365	.0288	.0211	.0134	.0057
−4.8	.0294	.0217	.0140	.0064	−0.8	.0367	.0290	.0213	.0136	.0059
−4.7	.0296	.0219	.0142	.0066	−0.7	.0369	.0292	.0215	.0138	.0061
−4.6	.0297	.0220	.0143	.0067	−0.6	.0371	.0294	.0218	.0140	.0063
−4.5	.0299	.0222	.0145	.0069	−0.5	.0373	.0296	.0220	0142	.0065
−4.4	.0301	.0224	.0147	.0071	−0.4	.0375	.0298	.0222	.0144	.0067
−4.3	.0302	.0225	.0148	.0072	−0.3	.3777	.0300	.0224	.0146	.0069
−4.2	.0304	.0227	.0150	.0074	−0.2	.0379	.0302	.0226	.0148	.0071
−4.1	.0306	.0229	.0152	.0076	−0.1	.0381	.0304	.0228	.0150	.0073
−4.0	.0307	.0230	.0153	.0077	−0.0	.0383	.0306	.0230	.0152	.0075

WET BULB 0° TO 4°.

Wet bulb.	0.0	1.0	2.0	3.0	4.0	5.0	6.0
0.0	0.0383	0.0306	0.0229	0.0152			
0.1	.0385	.0308	.0231	.0154			
0.2	.0387	.0310	.0233	.0156			
0.3	.0389	.0312	.0235	.0158			
0.4	.0391	.0314	.0237	.0160			
0.5	.0392	.0316	.0239	.0162			
0.6	.0394	.0318	.0241	.0164			
0.7	.0396	.0320	.0243	.0166			
0.8	.0398	.0322	.0245	.0168			
0.9	.0400	.0324	.0247	.0170			
1.0	.0403	.0326	.0249	.0172	0.0095		
1.1	.0405	.0328	.0251	.0174	.0096		
1.2	.0407	.0330	.0253	.0176	.0098		
1.3	.0409	.0332	.0255	.0178	.0100		
1.4	.0411	.0334	.0257	.0180	.0102		
1.5	.0413	.0336	.0259	.0182	.0104		
1.6	.0415	.0338	.0261	.0184	.0106		
1.7	.0417	.0340	.0263	.0186	.0108		
1.8	.0419	.0342	.0265	.0188	.0110		
1.9	.0421	.0344	.0267	.0190	.0112		
2.0	.0423	.0346	.0269	.0191	.0114	0.0037	
2.1	.0426	.0348	.0272	.0194	.0116	.0040	
2.2	.0428	.0351	.0274	.0196	.0119	.0042	
2.3	.0430	.0352	.0276	.0198	.0120	.0044	
2.4	.0431	.0354	.0277	.0199	.0122	.0045	
2.5	.0434	.0356	.0280	.0202	.0124	.0048	
2.6	.0436	.0359	.0282	.0204	.0127	.0050	
2.7	.0438	.0361	.0284	.0206	.0129	.0052	
2.8	.0440	.0363	.0286	.0208	.0131	.0054	
2.9	.0442	.0365	.0288	.0210	.0133	.0056	
3.0	.0444	.0367	.0290	.0212	.0135	.0058	
3.1	.0446	.0369	.0292	.0214	.0137	.0060	
3.2	.0449	.0372	.0295	.0217	.0140	.0063	
3.3	.0451	.0374	.0297	.0219	.0142	.0065	
3.4	.0453	.0376	.0299	.0221	.0144	.0067	
3.5	.0456	.0379	.0302	.0224	.0147	.0070	
3.6	.0458	.0381	.0304	.0226	.0149	.0072	
3.7	.0460	.0383	.0306	.0228	.0151	.0074	
3.8	.0462	.0385	.0308	.0230	.0153	.0076	
3.9	.0464	.0387	.0310	.0232	.0155	.0078	
4.0	.0467	.0390	.0313	.0235	.0158	.0081	0.0004

Proportional parts.	
Degrees.	*Inches.*
0.1	0.0008
.2	.0015
.3	.0023
.4	.0031
.5	.0039
.6	.0046
.7	.0054
.8	.0061
.9	.0069

TABLE 9.—*Vapor pressure, inches; barometer 21.42 inches; depression of wet bulb (T.—t'), °F*—Continued.

WET BULB 4° TO 8°.

Wet bulb.	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	Proportional parts.	
									Degrees.	*Inches.*
4.0	0.0467	0.0390	0.0313	0.0235	0.0158	0.0081	0.0004	....	0.1	0.0008
4.1	.0470	.0393	.0316	.0238	.0161	.0084	.0007	....	.2	.0015
4.2	.0472	.0395	.0318	.0240	.0163	.0086	.0009	....	.3	.0023
4.3	.0474	.0397	.0320	.0242	.0165	.0088	.0011	....	.4	.0031
4.4	.0476	.0399	.0322	.0244	.0167	.0090	.0013	....	.5	.0039
4.5	.0478	.0401	.0324	.0246	.0169	.0092	.0015	....	.6	.0046
4.6	.0481	.0404	.0327	.0249	.0172	.0095	.0018	....	.7	.0054
4.7	.0484	.0407	.0330	.0251	.0175	.0098	.0021	....	.8	.0062
4.8	.0486	.0409	.0332	.0253	.0177	.0100	.0023	....	.9	.0069
4.9	.0488	.0411	.0334	.0256	.0180	.0103	.0026	....		
5.0	.0491	.0414	.0336	.0259	.0182	.0106	.0027	....		
5.1	.0493	.0416	.0338	.0261	.0184	.0108	.0029	....		
5.2	.0495	.0418	.0340	.0263	.0186	.0110	.0031	....		
5.3	.0498	.0421	.0343	.0266	.0189	.0113	.0034	....		
5.4	.0500	.0423	.0345	.0268	.0190	.0115	.0036	....		
5.5	.0502	.0425	.0347	.0270	.0192	.0117	.0038	....		
5.6	.0505	.0428	.0350	.0273	.0195	.0120	.0041	....		
5.7	.0508	.0431	.0353	.0276	.0198	.0123	.0044	....		
5.8	.0510	.0433	.0355	.0278	.0200	.0125	.0046	....		
5.9	.0512	.0435	.0357	.0280	.0203	.0126	.0048	....		
6.0	.0515	.0438	.0360	.0283	.0206	.0128	.0051	....		
6.1	.0518	.0441	.0363	.0286	.0209	.0131	.0054	....		
6.2	.0520	.0443	.0365	.0288	.0211	.0133	.0056	....		
6.3	.0523	.0446	.0368	.0291	.0214	.0036	.0059	....		
6.4	.0526	.0449	.0371	.0294	.0217	.0139	.0062	....		
6.5	.0528	.0451	.0373	.0296	.0219	.0141	.0064	....		
6.6	.0531	.0454	.0376	.0299	.0222	.0144	.0067	....		
6.7	.0534	.0457	.0379	.0302	.0225	.0147	.0070	....		
6.8	.0536	.0459	.0381	.0304	.0227	.0150	.0072	....		
6.9	.0539	.0462	.0384	.0307	.0230	.0153	.0075	....		
7.0	.0542	.0465	.0387	.0310	.0233	.0155	.0078	....		
7.1	.0544	.0467	.0389	.0312	.0236	.0157	.0080	....		
7.2	.0547	.0470	.0392	.0315	.0239	.0160	.0083	....		
7.3	.0550	.0473	.0395	.0318	.0242	.0163	.0086	....		
7.4	.0553	.0476	.0398	.0321	.0245	.0166	.0089	....		
7.5	.0556	.0479	.0401	.0324	.0248	.0169	.0092	....		
7.6	.0558	.0481	.0403	.0326	.0250	.0171	.0094	....		
7.7	.0561	.0484	.0406	.0329	.0253	.0174	.0097	....		
7.8	.0564	.0487	.0409	.0332	.0256	.0177	.0100	....		
7.9	.0567	.0490	.0412	.0335	.0259	.0180	.0103	....		
8.0	.0570	.0493	.0415	.0338	.0262	.0184	.0106	0.0028		

WET BULB 8° TO 12°.

Wet bulb.	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	Proportional parts.	
											Deg.	*Ins.*
8.0	0.0570	0.0492	0.0415	0.0338	0.0260	0.0183	0.0106	0.0028	....	....	0.1	0.0008
8.1	.0573	.0495	.0418	.0341	.0263	.0186	.0109	.0031	....	....	.2	.0016
8.2	.0576	.0498	.0421	.0344	.0266	.0189	.0112	.0034	....	....	.3	.0023
8.3	.0579	.0501	.0424	.0347	.0269	.0192	.0115	.0037	....	....	.4	.0031
8.4	.0582	.0504	.0427	.0350	.0272	.0195	.0118	.0040	....	....	.5	.0039
8.5	.0584	.0506	.0429	.0352	.0274	.0197	.0120	.0043	....	....	.6	.0047
8.6	.0587	.0509	.0432	.0355	.0277	.0200	.0123	.0046	....	....	.7	.0054
8.7	.0590	.0512	.0435	.0358	.0280	.0203	.0126	.0049	....	....	.8	.0062
8.8	.0594	.0514	.0439	.0362	.0284	.0207	.0130	.0052	....	....	.9	.0070
8.9	.0597	.0518	.0442	.0365	.0287	.0210	.0132	.0055	....	....		
9.0	.0600	.0523	.0445	.0368	.0290	.0213	.0135	.0058	....	....		
9.1	.0603	.0526	.0448	.0371	.0293	.0216	.0138	.0061	....	....		
9.2	.0606	.0529	.0451	.0374	.0296	.0219	.0141	.0064	....	....		
9.3	.0609	.0532	.0454	.0377	.0299	.0222	.0144	.0067	....	....		
9.4	.0612	.0535	.0457	.0380	.0302	.0225	.0147	.0070	....	....		
9.5	.0615	.0538	.0461	.0383	.0306	.0028	.0151	.0073	....	....		
9.6	.0618	.0541	.0464	.0386	.0309	.0231	.0154	.0076	....	....		
9.7	.0622	.0545	.0468	.0390	.0313	.0235	.0158	.0080	....	....		
9.8	.0625	.0548	.0471	.0393	.0316	.0238	.0161	.0083	....	....		
9.9	.0628	.0550	.0474	.0396	.0318	.0240	.0164	.0086	....	....		
10.0	.0631	.0553	.0476	.0398	.0321	.0243	.0166	.0088	.0011	....		

TABLE 9.—*Vapor pressure, inches; barometer 21.42 inches; depression of wet bulb (T.—t'), °F*—Continued.

WET BULB 8° TO 12°—Continued.

Wet bulb.	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	Proportional parts.
10.1...	.0634	.0556	.0479	.0401	.0324	.0246	.0169	.0091	.0014	....	
10.2...	.0638	.0560	.0483	.0405	.0328	.0250	.0173	.0095	.0018	....	
10.3...	.0641	.0563	.0486	.0408	.0331	.0253	.0176	.0098	.0021	....	
10.4...	.0644	.0566	.0489	.0411	.0334	.0256	.0179	.0101	.0024	....	
10.5...	.0648	.0570	.0493	.0415	.0338	.0260	.0183	.0105	.0027	....	
10.6...	.0651	.0573	.0496	.0418	.0341	.0263	.0186	.0108	.0030	....	
10.7...	.0654	.0576	.0499	.0421	.0344	.0266	.0189	.0111	.0034	....	
10.8...	.0657	.0579	.0502	.0424	.0347	.0269	.0192	.0114	.0038	....	
10.9...	.0661	.0583	.0506	.0428	.0351	.0273	.0196	.0118	.0041	....	
11.0...	.0665	.0587	.0510	.0432	.0355	.0277	.0200	.0122	.0045	....	
11.1...	.0668	.0590	.0513	.0435	.0358	.0280	.0203	.0125	.0048	....	
11.2...	.0671	.0593	.0516	.0438	.0361	.0283	.0206	.0128	.0051	....	
11.3...	.0674	.0596	.0519	.0441	.0364	.0286	.0210	.0131	.0054	....	
11.4...	.0678	.0600	.0523	.0445	.0368	.0290	.0214	.0135	.0058	....	
11.5...	.0682	.0604	.0527	.0449	.0372	.0294	.0217	.0139	.0062	....	
11.6...	.0685	.0607	.0530	.0453	.0375	.0297	.0220	.0142	.0065	....	
11.7...	.0688	.0610	.0533	.0456	.0378	.0300	.0223	.0145	.0068	....	
11.8...	.0692	.0614	.0537	.0460	.0382	.0304	.0227	.0149	.0071	....	
11.9...	.0696	.0618	.0541	.0463	.0386	.0308	.0230	.0153	.0074	....	
12.0...	.0699	.0621	.0544	.0466	.0389	.0311	.0233	.0156	.0078	0.0001	

WET BULB 12° TO 16°.

Wet bulb.	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	Proportional parts.	
												Deg.	*Ins.*
12.0....	0.0699	0.0621	0.0544	0.0466	0.0389	0.0311	0.0233	0.0156	0.0078	0.0001	....	0.1	0.0008
12.1....	.0702	.0624	.0547	.0469	.0392	.0314	.0236	.0159	.0081	.0004	....	.2	.0015
12.2....	.0706	.0628	.0551	.0473	.0395	.0318	.0240	.0163	.0085	.0008	....	.3	.0023
12.3....	.0710	.0632	.0555	.0477	.0399	.0322	.0244	.0167	.0089	.0012	....	.4	.0031
12.4....	.0713	.0635	.0558	.0480	.0402	.0325	.0247	.0170	.0092	.0015	....	.5	.0039
12.5....	.0716	.0638	.0561	.0483	.0405	.0328	.0250	.0173	.0095	.0018	....	.6	.0047
12.6....	.0720	.0642	.0565	.0487	.0409	.0332	.0254	.0176	.0099	.0021	....	.7	.0054
12.7....	.0724	.0646	.0569	.0491	.0413	.0336	.0258	.0180	.0103	.0025	....	.8	.0062
12.8....	.0728	.0650	.0573	.0495	.0417	.0340	.0262	.0184	.0107	.0029	....	.9	.0070
12.9....	.0732	.0654	.0577	.0499	.0421	.0344	.0266	.0188	.0111	.0033	....		
13.0....	.0735	.0657	.0580	.0502	.0424	.0347	.0269	.0191	.0114	.0036	....		
13.1....	.0738	.0660	.0583	.0505	.0427	.0350	.0272	.0194	.0117	.0039	....		
13.2....	.0742	.0664	.0587	.0509	.0431	.0354	.0276	.0198	.0120	.0043	....		
13.3....	.0746	.0668	.0591	.0513	.0435	.0358	.0280	.0202	.0124	.0047	....		
13.4....	.0750	.0672	.0595	.0517	.0439	.0362	.0284	.0206	.0128	.0051	....		
13.5....	.0754	.0676	.0599	.0521	.0443	.0366	.0288	.0210	.0132	.0055	....		
13.6....	.0757	.0679	.0602	.0524	.0446	.0369	.0291	.0213	.0135	.0058	....		
13.7....	.0761	.0683	.0606	.0528	.0450	.0372	.0295	.0217	.0139	.0062	....		
13.8....	.0765	.0687	.0610	.0532	.0454	.0376	.0299	.0221	.0143	.0066	....		
13.9....	.0768	.0690	.0613	.0535	.0457	.0379	.0302	.0224	.0147	.0069	....		
14.0....	.0772	.0694	.0617	.0539	.0461	.0383	.0306	.0228	.0150	.0073	....		
14.1....	.0776	.0698	.0621	.0543	.0465	.0387	.0310	.0232	.0154	.0077	....		
14.2....	.0780	.0702	.0625	.0547	.0469	.0391	.0314	.0236	.0158	.0081	....		
14.3....	.0784	.0706	.0629	.0551	.0473	.0395	.0318	.0240	.0162	.0083	....		
14.4....	.0787	.0709	.0632	.0554	.0476	.0398	.0321	.0243	.0165	.0086	....		
14.5....	.0790	.0712	.0635	.0557	.0479	.0401	.0324	.0246	.0168	.0090	....		
14.6....	.0794	.0716	.0639	.0561	.0483	.0405	.0427	.0250	.0172	.0094	....		
14.7....	.0798	.0720	.0642	.0565	.0487	.0409	.0431	.0254	.0176	.0098	....		
14.8....	.0802	.0724	.0646	.0569	.0491	.0413	.0435	.0258	.0180	.0102	....		
14.9....	.0806	.0728	.0650	.0573	.0495	.0417	.0439	.0262	.0184	.0106	....		
15.0....	.0810	.0732	.0654	.0577	.0499	.0421	.0343	.0266	.0188	.0110	0.0034		
15.1....	.0814	.0736	.0658	.0581	.0503	.0425	.0347	.0270	.0192	.0114	.0038		
15.2....	.0818	.0740	.0662	.0585	.0507	.0429	.0351	.0274	.0196	.0118	.0042		
15.3....	.0822	.0744	.0666	.0589	.0511	.0433	.0355	.0278	.0200	.0122	.0046		
15.4....	.0826	.0748	.0670	.0593	.0515	.0437	.0359	.0282	.0204	.0126	.0050		
15.5....	.0830	.0752	.0674	.0597	.0519	.0441	.0363	.0285	.0208	.0130	.0053		
15.6....	.0834	.0756	.0678	.0601	.0523	.0445	.0367	.0289	.0212	.0134	.0057		
15.7....	.0838	.0760	.0682	.0605	.0527	.0449	.0371	.0293	.0216	.0138	.0060		
15.8....	.0842	.0764	.0686	.0609	.0531	.0453	.0375	.0297	.0220	.0142	.0064		
15.9....	.0846	.0768	.0690	.0613	.0535	.0457	.0379	.0301	.0224	.0146	.0068		
16.0....	.0850	.0772	.0694	.0617	.0539	.0461	.0383	.0305	.0228	.0150	.0072		

TABLE 9.—*Vapor pressure, inches; barometer 21.42 inches; depression of wet bulb (T.—t′), °F*—Continued.

WET BULB 16° TO 20°.

Wet bulb.	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
16.0	0.0850	0.0772	0.0694	0.0617	0.0539	0.0461	0.0383	0.0305	0.0228	0.0150	0.0072
16.1	.0854	.0776	.0698	.0621	.0543	.0465	.0387	.0309	.0232	.0154	....
16.2	.0857	.0779	.0701	.0625	.0546	.0468	.0390	.0312	.0236	.0157	....
16.3	.0862	.0784	.0706	.0629	.0551	.0473	.0395	.0317	.0240	.0162	....
16.4	.0866	.0788	.0710	.0633	.0555	.0477	.0399	.0321	.0244	.0166	....
16.5	.0870	.0792	.0714	.0637	.0559	.0481	.0403	.0325	.0248	.0169	....
16.6	.0874	.0796	.0718	.0641	.0563	.0485	.0407	.0329	.0252	.0173	....
16.7	.0878	.0800	.0722	.0645	.0567	.0489	.0411	.0333	.0256	.0177	....
16.8	.0882	.0804	.0726	.0649	.0571	.0493	.0415	.0337	.0260	.0181	....
16.9	.0886	.0808	.0730	.0653	.0575	.0497	.0419	.0341	.0264	.0185	....
17.0	.0891	.0813	.0735	.0657	.0580	.0502	.0424	.0346	.0268	.0190	.0112
17.1	.0895	.0817	.0739	.0661	.0584	.0506	.0428	.0350	.0272	.0194	.0116
17.2	.0899	.0821	.0743	.0665	.0588	.0510	.0432	.0354	.0276	.0198	.0120
17.3	.0903	.0825	.0747	.0669	.0592	.0514	.0436	.0358	.0280	.0202	.0124
17.4	.0907	.0829	.0751	.0673	.0596	.0518	.0440	.0362	.0284	.0206	.0128
17.5	.0912	.0834	.0756	.0678	.0600	.0522	.0445	.0367	.0289	.0211	.0133
17.6	.0916	.0838	.0760	.0682	.0604	.0526	.0449	.0371	.0293	.0215	.0137
17.7	.0920	.0842	.0764	.0686	.0608	.0530	.0453	.0375	.0297	.0219	.0141
17.8	.0925	.0847	.0769	.0691	.0613	.0535	.0458	.0380	.0302	.0224	.0146
17.9	.0929	.0851	.0773	.0695	.0617	.0539	.0462	.0384	.0306	.0228	.0150
18.0	.0933	.0855	.0777	.0699	.0621	.0543	.0466	.0388	.0310	.0232	.0154
18.1	.0938	.0860	.0782	.0704	.0626	.0548	.0471	.0392	.0314	.0236	.0158
18.2	.0842	.0864	.0786	.0708	.0630	.0552	.0475	.0396	.0318	.0240	.0162
18.3	.0946	.0868	.0790	.0712	.0634	.0556	.0479	.0400	.0322	.0244	.0166
18.4	.0951	.0873	.0795	.0717	.0639	.0561	.0484	.0405	.0327	.0249	.0171
18.5	.0956	.0878	.0800	.0722	.0644	.0566	.0488	.0410	.0332	.0254	.0176
18.6	.0960	.0882	.0804	.0726	.0648	.0570	.0492	.0414	.0336	.0258	.0180
18.7	.0964	.0886	.0808	.0730	.0652	.0574	.0496	.0418	.0340	.0262	.0184
18.8	.0969	.0891	.0813	.0735	.0657	.0579	.0501	.0423	.0345	.0267	.0189
18.9	.0974	.0896	.0818	.0740	.0662	.0584	.0506	.0428	.0350	.0272	.0194
19.0	.0979	.0901	.0823	.0745	.0667	.0589	.0511	.0433	.0355	.0277	.0199
19.1	.0984	.0906	.0828	.0750	.0672	.0594	.0516	.0438	.0360	.0282	.0203
19.2	.0988	.0910	.0832	.0754	.0676	.0598	.0520	.0442	.0364	.0286	.0207
19.3	.0992	.0914	.0836	.0758	.0680	.0602	.0524	.0446	.0368	.0290	.0211
19.4	.0998	.0920	.0842	.0764	.0686	.0608	.0530	.0452	.0374	.0296	.0217
19.5	.1002	.0924	.0846	.0768	.0690	.0612	.0534	.0456	.0378	.0300	.0221
19.6	.1007	.0929	.0851	.0773	.0695	.0617	.0539	.0461	.0383	.0305	.0226
19.7	.1012	.0934	.0856	.0778	.0700	.0622	.0544	.0466	.0388	.0310	.0231
19.8	.1017	.0939	.0861	.0783	.0705	.0627	.0549	.0471	.0393	.0315	.0236
19.9	.1022	.0944	.0866	.0788	.0710	.0632	.0554	.0476	.0398	.0320	.0241
20.0	.1026	.0948	.0870	.0792	.0714	.0636	.0558	.0480	.0402	.0324	.2045

TABLE 9.—*Vapor pressure, inches; barometer 21.42 inches; depression of wet bulb (T.—t'), °F*—Continued.

WET BULB 20° TO 24°.

Wet bulb.	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0
20.0	0.1026	0.0948	0.0870	0.0792	0.0714	0.0636	0.0558	0.0480	0.0402	0.0324	0.0245	0.0168	0.0090	0.0012	....
20.1	.1031	.0953	.0875	.0797	.0719	.0641	.0563	.0485	.0407	.0329	.0250	.0173	.0095	.0017	....
20.2	.1036	.0958	.0880	.0802	.0724	.0646	.0568	.0490	.0412	.0334	.0255	.0178	.0100	.0022	....
20.3	.1041	.0963	.0885	.0807	.0729	.0651	.0573	.0495	.0417	.0339	.0260	.0183	.0105	.0027	....
20.4	.1046	.0968	.0890	.0812	.0734	.0656	.0578	.0500	.0422	.0344	.0265	.0188	.0110	.0032	....
20.5	.1051	.0973	.0895	.0817	.0739	.0661	.0583	.0505	.0427	.0349	.0270	.0193	.0115	.0037	....
20.6	.1056	.0978	.0900	.0822	.0744	.0666	.0588	.0510	.0432	.0354	.0275	.0198	.0120	.0042	....
20.7	.1062	.0984	.0906	.0828	.0750	.0672	.0594	.0516	.0438	.0360	.0281	.0203	.0125	.0047	....
20.8	.1067	.0989	.0911	.0833	.0755	.0677	.0599	.0521	.0443	.0365	.0286	.0208	.0130	.0052	....
20.9	.1072	.0994	.0916	.0838	.0760	.0682	.0604	.0526	.0448	.0369	.0291	.0213	.0135	.0057	....
21.0	.1077	.0999	.0921	.0843	.0765	.0687	.0609	.0531	.0453	.0374	.0296	.0218	.0140	.0062	....
21.1	.1082	.1004	.0926	.0848	.0770	.0692	.0614	.0536	.0458	.0379	.0301	.0223	.0145	.0067	....
21.2	.1087	.1009	.0931	.0853	.0775	.0697	.0619	.0541	.0463	.0384	.0306	.0228	.0150	.0072	....
21.3	.1092	.1015	.0936	.0858	.0780	.0702	.0624	.0546	.0468	.0389	.0311	.0233	.0155	.0077	....
21.4	.1098	.1020	.0942	.0864	.0786	.0708	.0629	.0551	.0473	.0395	.0317	.0239	.0161	.0083	....
21.5	.1103	.1025	.0947	.0869	.0791	.0713	.0634	.0556	.0478	.0400	.0322	.0244	.0166	.0088	....
21.6	.1108	.1030	.0952	.0874	.0796	.0718	.0639	.0561	.0483	.0405	.0327	.0249	.0171	.0093	....
21.7	.1114	.1036	.0958	.0880	.0802	.0724	.0645	.0567	.0489	.0411	.0333	.0255	.0177	.0099	....
21.8	.1119	.1041	.0963	.0885	.0807	.0729	.0650	.0572	.0494	.0416	.0338	.0260	.0182	.0104	....
21.9	.1124	.1046	.0968	.0890	.0812	.0734	.0655	.0577	.0499	.0421	.0343	.0265	.0187	.0109	....
22.0	.1130	.1052	.0974	.0896	.0818	.0739	.0661	.0583	.0505	.0427	.0349	.0271	.0193	.0115	....
22.1	.1136	.1058	.0980	.0902	.0823	.0745	.0666	.0589	.0511	.0433	.0354	.0276	.0198	.0120	....
22.2	.1141	.1063	.0985	.0907	.0828	.0750	.0671	.0594	.0516	.0438	.0359	.0282	.0204	.0126	....
22.3	.1146	.1068	.0990	.0912	.0833	.0755	.0676	.0599	.0521	.0443	.0364	.0287	.0209	.0131	....
22.4	.1152	.1074	.0996	.0918	.0839	.0761	.0682	.0605	.0527	.0449	.0370	.0292	.0214	.0136	....
22.5	.1158	.1080	.1002	.0924	.0845	.0767	.0688	.0611	.0533	.0455	.0376	.0298	.0220	.0142	....
22.6	.1163	.1085	.1007	.0929	.0850	.0772	.0693	.0616	.0538	.0460	.0381	.0303	.0225	.0147	....
22.7	.1168	.1090	.1012	.0934	.0855	.0777	.0698	.0621	.0543	.0465	.0386	.0308	.0230	.0152	....
22.8	.1174	.1096	.1018	.0940	.0861	.0783	.0704	.0627	.0549	.0471	.0392	.0314	.0236	.0158	....
22.9	.1180	.1102	.1024	.0946	.0866	.0789	.0710	.0633	.0554	.0477	.0398	.0320	.0242	.0164	....
23.0	.1185	.1107	.1029	.0951	.0872	.0794	.0716	.0638	.0560	.0482	.0403	.0325	.0247	.0169	0.0091
23.1	.1190	.1112	.1034	.0956	.0877	.0799	.0721	.0643	.0565	.0487	.0408	.0330	.0252	.0174	.0096
23.2	.1196	.1118	.1040	.0962	.0883	.0805	.0727	.0648	.0570	.0492	.0414	.0336	.0257	.0179	.0101
23.3	.1202	.1124	.1046	.0968	.0889	.0811	.0733	.0654	.0576	.0498	.0420	.0341	.0263	.0185	.0197
23.4	.1207	.1129	.1051	.0973	.0894	.0816	.0738	.0659	.0581	.0503	.0425	.0347	.0268	.0190	.0112
23.5	.1213	.1135	.1057	.0979	.0900	.0822	.0744	.0665	.0587	.0509	.0431	.0354	.0274	.0196	.0118
23.6	.1219	.1141	.1063	.0985	.0906	.0828	.0750	.0671	.0593	.0515	.0437	.0359	.0280	.0202	.0124
23.7	.1224	.1146	.1068	.0900	.0911	.0833	.0755	.0676	.0598	.0520	.0442	.0365	.0285	.0207	.0129
23.8	.1230	.1152	.1074	.0996	.0917	.0839	.0761	.0682	.0604	.0526	.0448	.0372	.0291	.0213	.0135
23.9	.1236	.1158	.1080	.1002	.0923	.0845	.0767	.0688	.0610	.0532	.0454	.0377	.0297	.0219	.0141
24.0	.1242	.1164	.1086	.1007	.0929	.0851	.0773	.0694	.0616	.0538	.0460	.0382	.0303	.0225	.0147

Proportional parts.

Degrees.	*Inches.*
0.1	0.0008
.2	.0016
.3	.0023
.4	.0031
.5	.0039
.6	.0047
.7	.0055
.8	.0062
.9	.0070

TABLE 9.—*Vapor pressure, inches; barometer 21.42 inches; depression of wet bulb (T.—t'), °F*—Continued.

Vapor pressure, inches; barometer, 21.42 inches; depression of wet bulb ($T-t'$), °F.

WET BULB, 24° TO 28°.

Wet bulb.	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0
24.0	0.1242	0.1164	0.1086	0.1007	0.0929	0.0851	0.0773	0.0694	0.0616	0.0538	0.0460	0.0382	0.0303	0.0225	0.0147	....	....
24.1	.1248	.1170	.1092	.1013	.0935	.0857	.0779	.0700	.0622	.0544	.0466	.0387	.0309	.0231	.0153	....	....
24.2	.1254	.1176	.1098	.1019	.0941	.0863	.0785	.0706	.0628	.0550	.0472	.0393	.0315	.0237	.0159	....	....
24.3	.1260	.1182	.1104	.1025	.0947	.0869	.0791	.0712	.0634	.0556	.0478	.0399	.0321	.0243	.0165	....	....
24.4	.1266	.1188	.1110	.1031	.0953	.0875	.0797	.0718	.0640	.0562	.0484	.0405	.0327	.0249	.0171	....	....
24.5	.1272	.1194	.1116	.1037	.0959	.0881	.0803	.0724	.0648	.0568	.0490	.0411	.0333	.0255	.0177	....	....
24.6	.1278	.1200	.1121	.1043	.0965	.0887	.0808	.0730	.0654	.0574	.0495	.0417	.0339	.0261	.0183	....	....
24.7	.1284	.1206	.1127	.1049	.0971	.0893	.0814	.0736	.0660	.0580	.0501	.0423	.0345	.0267	.0189	....	....
24.8	.1290	.1212	.1133	.1055	.0977	.0899	.0820	.0742	.0666	.0586	.0507	.0429	.0351	.0273	.0195	....	....
24.9	.1296	.1218	.1139	.1061	.0983	.0905	.0824	.0748	.0672	.0592	.0513	.0435	.0357	.0279	.0201	....	....
25.0	.1302	.1224	.1145	.1067	.0989	.0911	.0832	.0754	.0676	.0598	.0519	.0441	.0363	.0285	.0206	0.0128	0.0050
25.1	.1308	.1230	.1151	.1073	.0995	.0917	.0838	.0760	.0682	.0604	.0525	.0447	.0369	.0291	.0212	.0134	.0056
25.2	.1314	.1236	.1157	.1079	.1001	.0923	.0844	.0766	.0688	.0610	.0531	.0453	.0375	.0297	.0218	.0140	.0062
25.3	.1320	.1242	.1163	.1085	.1007	.0929	.0850	.0772	.0694	.0616	.0537	.0459	.0381	.0303	.0224	.0146	.0068
25.4	.1327	.1249	.1170	.1092	.1014	.0936	.0857	.0779	.0701	.0623	.0544	.0466	.0388	.0310	.0231	.0153	.0074
25.5	.1333	.1255	.1176	.1098	.1020	.0942	.0863	.0785	.0707	.0629	.0550	.0472	.0394	.0316	.0237	.0159	.0081
25.6	.1339	.1261	.1182	.1104	.1026	.0948	.0869	.0791	.0713	.0635	.0556	.0478	.0400	.0322	.0243	.0165	.0087
25.7	.1346	.1268	.1189	.1111	.1033	.0955	.0876	.0798	.0720	.0642	.0563	.0485	.0407	.0329	.0250	.0172	.0094
25.8	.1352	.1274	.1195	.1117	.1039	.0961	.0882	.0804	.0726	.0648	.0569	.0491	.0413	.0335	.0256	.0178	.0100
25.9	.1368	.1280	.1201	.1123	.1045	.0967	.0888	.0810	.0732	.0654	.0575	.0498	.0419	.0341	.0263	.0184	.0106
26.0	.1365	.1287	.1208	.1130	.1052	.0973	.0895	.0817	.0739	.0660	.0582	.0504	.0425	.0347	.0269	.0190	.0112
26.1	.1371	.1293	.1214	.1136	.1058	.0979	.0901	.0823	.0745	.0666	.0588	.0510	.0431	.0353	.0275	.0196	.0118
26.2	.1377	.1299	.1220	.1142	.1064	.0985	.0907	.0829	.0751	.0672	.0594	.0516	.0437	.0359	.0281	.0202	.0124
26.3	.1384	.1306	.1227	.1149	.1071	.0992	.0914	.0836	.0758	.0679	.0601	.0523	.0444	.0366	.0288	.0209	.0131
26.4	.1390	.1312	.1233	.1155	.1077	.0998	.0920	.0842	.0764	.0685	.0607	.0529	.0450	.0372	.0294	.0215	.0137
26.5	.1396	.1318	.1239	.1161	.1083	.1004	.0926	.0848	.0770	.0691	.0613	.0535	.0456	.0378	.0300	.0221	.0143
26.6	.1403	.1325	.1246	.1168	.1090	.1011	.0933	.0855	.0777	.0698	.0620	.0542	.0463	.0385	.0307	.0228	.0150
26.7	.1410	.1332	.1253	.1175	.1097	.1018	.0940	.0862	.0784	.0705	.0627	.0549	.0470	.0392	.0314	.0235	.0157
26.8	.1416	.1338	.1259	.1181	.1103	.1024	.0946	.0868	.0790	.0711	.0633	.0555	.0476	.0398	.0320	.0241	.0163
26.9	.1423	.1345	.1266	.1188	.1110	.1031	.0953	.0875	.0797	.0718	.0640	.0562	.0483	.0405	.0327	.0248	.0170
27.0	.1430	.1352	.1273	.1195	.1117	.1038	.0960	.0881	.0803	.0725	.0646	.0568	.0490	.0411	.0333	.0255	.0176
27.1	.1436	.1358	.1279	.1201	.1123	.1044	.0966	.0887	.0809	.0731	.0652	.0574	.0496	.0417	.0339	.0262	.0182
27.2	.1443	.1365	.1286	.1208	.1130	.1051	.0973	.0894	.0816	.0738	.0659	.0581	.0503	.0424	.0346	.0269	.0189
27.3	.1450	.1372	.1293	.1215	.1137	.1058	.0980	.0901	.0823	.0745	.0666	.0588	.0510	.0431	.0353	.0276	.0196
27.4	.1456	.1378	.1299	.1221	.1143	.1064	.0986	.0907	.0829	.0751	.0672	.0594	.0516	.0437	.0359	.0282	.0202
27.5	.1463	.1385	.1306	.1228	.1150	.1071	.0993	.0914	.0836	.0758	.0679	.0601	.0523	.0444	.0366	.0289	.0209
27.6	.1470	.1392	.1313	.1233	.1157	.1078	.1000	.0921	.0843	.0765	.0686	.0608	.0530	.0451	.0373	.0296	.0216
27.7	.1476	.1398	.1319	.1241	.1163	.1084	.1006	.0927	.0849	.0771	.0692	.0614	.0536	.0457	.0379	.0302	.0222
27.8	.1483	.1405	.1326	.1248	.1170	.1091	.1013	.0934	.0856	.0778	.0699	.0621	.0543	.0464	.0386	.0309	.0229
27.9	.1490	.1412	.1333	.1255	.1177	.1098	.1020	.0941	.0863	.0785	.0706	.0628	.0549	.0471	.0393	.0316	.0236
28.0	.1497	.1419	.1340	.1262	.1183	.1105	.1027	.0948	.0870	.0791	.0713	.0634	.0556	.0478	.0399	.0321	.0242

Proportional parts.	
Degrees.	*Inches.*
0.1	0.0008
.2	.0016
.3	.0024
.4	.0031
.5	.0039
.6	.0047
.7	.0055
.8	.0063
.9	.0071

TABLE 9.—*Vapor pressure, inches; barometer 21.42 inches; depression of wet bulb (T.—t′), °F*—Continued.

WET BULB 28° TO 32°.

Wet Bulb.	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0	21.0	22.0
28.1	0.1504	0.1426	0.1347	0.1269	0.1190	0.1112	0.1034	0.0955	0.0877	0.0798	0.0720	0.0641	0.0563	0.0485	0.0406	0.0328	0.0250	......	......	......	......	......	......
28.2	.1511	.1433	.1354	.1276	.1197	.1119	.1041	.0962	.0884	.0805	.0727	.0648	.0570	.0492	.0413	.0335	.0257	......	......	......	......	......	......
28.3	.1518	.1440	.1361	.1283	.1204	.1126	.1048	.0969	.0891	.0812	.0734	.0655	.0577	.0499	.0420	.0342	.0264	......	......	......	......	......	......
28.4	.1525	.1448	.1369	.1291	.1212	.1134	.1055	.0977	.0898	.0820	.0741	.0662	.0584	.0506	.0427	.0349	.0271	......	......	......	......	......	......
28.5	.1532	.1455	.1376	.1298	.1219	.1141	.1062	.0984	.0905	.0827	.0748	.0669	.0591	.0513	.0434	.0356	.0278	......	......	......	......	......	......
28.6	.1539	.1462	.1383	.1305	.1226	.1148	.1069	.0991	.0912	.0834	.0755	.0676	.0598	.0520	.0441	.0363	.0285	......	......	......	......	......	......
28.7	.1546	.1469	.1390	.1312	.1233	.1155	.1076	.0998	.0919	.0841	.0762	.0683	.0605	.0527	.0448	.0370	.0292	......	......	......	......	......	......
28.8	.1554	.1477	.1397	.1319	.1240	.1162	.1083	.1005	.0848	.0848	.0769	.0691	.0613	.0535	.0456	.0378	.0300	......	......	......	......	......	......
28.9	.1561	.1484	.1404	.1326	.1247	.1169	.1090	.1012	.0933	.0855	.0776	.0698	.0620	.0542	.0463	.0385	.0307	......	......	......	......	......	......
29.0	.1568	.1490	.1411	.1333	.1254	.1176	.1097	.1019	.0940	.0862	.0783	.0705	.0626	.0548	.0470	.0391	.0313	......	......	......	......	......	......
29.1	.1575	.1497	.1419	.1340	.1262	.1183	.1105	.1026	.0948	.0869	.0791	.0712	.0633	.0555	.0470	.0398	.0320	......	......	......	......	......	......
29.2	.1582	.1504	.1426	.1347	.1269	.1190	.1112	.1033	.0955	.0876	.0798	.0719	.0640	.0562	.0477	.0405	.0327	......	......	......	......	......	......
29.3	.1589	.1511	.1433	.1354	.1276	.1197	.1119	.1040	.0962	.0883	.0805	.0726	.0647	.0569	.0484	.0412	.0334	......	......	......	......	......	......
29.4	.1596	.1518	.1440	.1361	.1283	.1204	.1126	.1047	.0969	.0890	.0812	.0733	.0654	.0576	.0491	.0419	.0340	......	......	......	......	......	......
29.5	.1604	.1526	.1448	.1369	.1291	.1212	.1134	.1055	.0977	.0898	.0820	.0741	.0662	.0584	.0499	.0427	.0348	......	......	......	......	......	......
29.6	.1611	.1533	.1455	.1377	.1298	.1219	.1141	.1062	.0984	.0905	.0827	.0748	.0669	.0591	.0506	.0434	.0355	......	......	......	......	......	......
29.7	.1618	.1540	.1462	.1384	.1305	.1226	.1148	.1069	.0991	.0912	.0834	.0755	.0676	.0598	.0513	.0441	.0362	......	......	......	......	......	......
29.8	.1626	.1548	.1470	.1392	.1313	.1234	.1156	.1077	.0999	.0920	.0842	.0763	.0684	.0606	.0521	.0448	.0370	......	......	......	......	......	......
29.9	.1634	.1556	.1477	.1399	.1321	.1242	.1164	.1085	.1007	.0928	.0850	.0771	.0692	.0614	.0529	.0456	.0378	......	......	......	......	......	......
30.0	.1641	.1563	.1485	.1406	.1328	.1249	.1171	.1092	.1014	.0935	.0857	.0777	.0699	.0620	.0542	.0463	.0385	0.031	0.023	0.015	0.004	......	......
30.1	.1648	.1570	.1493	.1413	.1335	.1256	.1178	.1099	.1021	.0942	.0864	.079	.071	.063	.055	.047	.039	.032	.024	.016	.005	......	......
30.2	.1656	.1579	.1501	.1421	.1343	.1264	.1186	.1107	.1029	.0950	.0871	.080	.072	.064	.056	.048	.040	.033	.025	.017	.006	......	......
30.3	.1664	.1586	.1508	.1428	.1351	.1272	.1194	.1115	.1037	.0958	.0879	.080	.072	.064	.056	.048	.040	.033	.025	.017	.008	......	......
30.4	.1671	.1594	.1515	.1435	.1358	.1279	.1201	.1122	.1044	.0965	.0886	.081	.073	.065	.057	.049	.041	.034	.026	.018	.009	......	......
30.5	.1679	.1602	.1522	.1442	.1366	.1287	.1209	.1130	.1052	.0973	.0894	.082	.074	.066	.058	.050	.042	.035	.027	.019	.011	......	......
30.6	.1687	.1609	.1529	.1450	.1373	.1295	.1217	.1138	.1060	.0981	.0902	.083	.075	.067	.059	.051	.043	.036	.028	.020	.012	......	......
30.7	.1694	.1617	.1537	.1458	.1381	.1302	.1224	.1145	.1067	.0988	.0909	.083	.075	.067	.059	.051	.043	.036	.028	.020	.013	......	......
30.8	.1702	.1625	.1545	.1466	.1388	.1310	.1232	.1153	.1075	.0995	.0917	.084	.076	.068	.060	.052	.044	.037	.029	.021	.014	......	......
30.9	.1710	.1632	.1553	.1474	.1396	.1318	.1240	.1161	.1083	.1003	.0925	.085	.077	.069	.061	.053	.045	.037	.029	.022	.014	......	......
31.0	.1718	.1639	.1561	.1482	.1404	.1325	.1247	.1168	.1090	.1011	.0932	.085	.078	.070	.062	.054	.046	.038	.030	.023	.015	0.007	......
31.1	.1726	.1647	.1569	.1490	.1412	.1333	.1255	.1176	.1098	1019	.0940	.086	.079	.071	.063	.055	.047	.039	.031	024	.016	.008	......
31.2	.1734	.1655	.1577	.1498	.1420	.1341	.1263	.1184	.1106	.1027	.0948	.086	.079	.071	.063	.055	.047	.039	.031	.024	.016	.008	......
31.3	.1742	.1663	.1585	.1506	.1428	.1349	.1271	.1192	.1114	.1035	.0956	.087	.080	.072	.064	.056	.048	.040	.032	.025	.017	.009	......
31.4	.1750	.1671	.1593	.1514	.1436	.1357	.1279	.1200	.1122	.1043	.0964	.088	.081	.073	.065	.057	.049	.041	.033	.026	.018	.010	......
31.5	.1758	.1679	.1601	.1522	.1444	.1365	.1287	.1208	.1130	.1051	.0972	.089	.082	.074	.066	.058	.050	.042	.034	.027	.019	.011	......
31.6	.1766	.1687	.1609	.1530	.1452	.1373	.1295	.1216	.1138	.1059	.0980	.090	.083	.075	.067	.059	.051	.043	.035	.028	.020	.012	......
31.7	.1774	.1695	.1617	.1538	.1460	.1381	.1303	.1224	.1146	.1067	.0988	.090	.083	.075	.067	.059	.051	.043	.035	.028	.020	.012	......
31.8	.1782	.1703	.1625	.1546	.1468	.1389	.1311	.1232	.1154	.1075	.0996	.091	.084	.076	.068	.060	.052	.044	.036	.029	.021	.013	......
31.9	.1790	.1711	.1633	.1554	.1476	.1397	.1319	.1240	.1162	.1083	.1004	.092	.085	.077	.069	.061	.053	.045	.037	.030	.022	.014	......
32.0	.1798	.1719	.1640	.1562	.1484	.1405	.1326	.1248	.1169	.1091	.1012	.093	.085	.078	.070	.062	.054	.046	.038	.030	.023	.015	.007

Proportional parts.	
Deg.	*Ins.*
0.1	0.0008
.2	.0016
.3	.0024
.4	.0031
.5	.0039
.6	.0047
.7	.0055
.8	.0063
.9	.0071

TABLE 9.—*Vapor pressure, inches; barometer 21.42 inches; depression of wet bulb (T.—t′), °F*—Continued.

WET BULB 32° TO 36°.

Wet bulb.	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0	21.0	22.0	23.0	24.0
32.1	0.181	0.173	0.165	0.157	0.149	0.141	0.134	0.126	0.118	0.110	0.102	0.094	0.086	0.079	0.071	0.063	0.055	0.047	0.039	0.031	0.024	0.016	0.008	......	......
32.2	.181	.173	.165	.157	.149	.141	.134	.126	.118	.110	.102	.094	.086	.079	.071	.063	.055	.047	.039	.031	.024	.016	.008	......	......
32.3	.182	.174	.166	.158	.150	.142	.135	.127	.119	.111	.103	.095	.087	.080	.072	.064	.056	.048	.040	.032	.025	.017	.009	......	......
32.4	.183	.175	.167	.159	.151	.143	.136	.128	.120	.112	.104	.096	.088	.081	.073	.065	.057	.049	.041	.033	.026	.018	.010	......	......
32.5	.184	.176	.168	.160	.152	.144	.137	.129	.121	.113	.105	.097	.089	.082	.074	.066	.058	.050	.042	.034	.027	.019	.011	......	......
32.6	.184	.176	.168	.160	.152	.144	.137	.129	.121	.113	.105	.097	.089	.082	.074	.066	.058	.050	.042	.034	.027	.019	.011	......	......
32.7	.185	.177	.169	.161	.153	.145	.138	.130	.122	.114	.106	.098	.090	.083	.075	.067	.059	.051	.043	.035	.028	.020	.012	......	......
32.8	.186	.178	.170	.162	.154	.146	.139	.131	.123	.115	.107	.098	.090	.083	.075	.067	.059	.051	.043	.036	.029	.021	.013	......	......
32.9	.186	.178	.170	.162	.155	.147	.139	.131	.123	.115	.107	.099	.091	.084	.076	.068	.060	.052	.044	.037	.030	.021	.013	......	......
33.0	.187	.179	.171	.163	.156	.148	.140	.132	.124	.116	.108	.100	.093	.085	.077	.069	.061	.053	.045	.038	.030	.022	.014	......	......
33.1	.188	.180	.172	.164	.157	.149	.141	.133	.125	.117	.109	.101	.094	.086	.078	.070	.062	.054	.046	.039	.031	.023	.015	......	......
33.2	.189	.181	.173	.165	.158	.150	.142	.134	.126	.118	.110	.102	.095	.087	.079	.071	.063	.055	.047	.040	.032	.024	.016	......	......
33.3	.190	.182	.174	.166	.159	.151	.143	.135	.127	.119	.111	.103	.096	.088	.080	.072	.064	.056	.048	.041	.033	.025	.017	......	......
33.4	.190	.182	.174	.166	.159	.151	.143	.135	.127	.119	.111	.103	.096	.088	.080	.072	.064	.056	.048	.041	.033	.025	.017	......	......
33.5	.191	.183	.175	.167	.160	.152	.144	.136	.128	.120	.112	.104	.097	.089	.081	.073	.065	.057	.049	.042	.034	.026	.018	......	......
33.6	.192	.184	.176	.168	.161	.153	.145	.137	.129	.121	.113	.105	.098	.090	.082	.074	.066	.058	.050	.043	.035	.027	.019	......	......
33.7	.193	.185	.177	.169	.162	.154	.146	.138	.130	.122	.114	.106	.099	.091	.083	.075	.067	.059	.051	.044	.036	.028	.020	......	......
33.8	.193	.185	.177	.169	.162	.154	.146	.138	.130	.122	.114	.106	.099	.091	.083	.075	.067	.059	.051	.044	.036	.028	.020	......	......
33.9	.194	.186	.178	.170	.163	.155	.147	.139	.131	.123	.115	.107	.100	.092	.084	.076	.068	.060	.052	.045	.037	.029	.021	......	......
34.0	.195	.187	.179	.171	.164	.156	.148	.140	.132	.124	.116	.108	.100	.093	.085	.077	.069	.061	.053	.045	.038	.030	.022	......	......
34.1	.196	.188	.180	.172	.165	.157	.149	.141	.133	.125	.117	.109	.101	.094	.086	.078	.070	.062	.054	.046	.039	.031	.023	......	......
34.2	.196	.188	.180	.172	.165	.157	.149	.141	.133	.125	.117	.109	.101	.094	.086	.078	.070	.062	.054	.046	.039	.031	.023	......	......
34.3	.197	.189	.181	.173	.166	.158	.150	.142	.134	.126	.118	.110	.102	.095	.087	.079	.071	.063	.055	.047	.040	.032	.024	......	......
34.4	.198	.190	.182	.174	.167	.159	.151	.143	.135	.127	.119	.111	.103	.096	.088	.080	.072	.064	.056	.048	.041	.033	.025	......	......
34.5	.199	.191	.183	.175	.168	.160	.152	.144	.136	.128	.120	.112	.104	.097	.089	.081	.073	.065	.057	.049	.042	.034	.026	......	......
34.6	.200	.192	.184	.176	.169	.161	.153	.145	.137	.129	.121	.113	.105	.098	.090	.082	.074	.066	.058	.050	.043	.035	.027	......	......
34.7	.200	.192	.184	.176	.169	.161	.153	.145	.137	.129	.121	.113	.105	.098	.090	.082	.074	.067	.059	.051	.044	.036	.028	......	......
34.8	.201	.193	.185	.177	.170	.162	.154	.146	.138	.130	.122	.114	.106	.099	.091	.083	.075	.068	.060	.052	.044	.037	.029	......	......
34.9	.202	.194	.186	.178	.171	.163	.155	.147	.139	.131	.123	.115	.107	.100	.092	.084	.076	.069	.061	.053	.045	.038	.030	......	......
35.0	.203	.195	.187	.179	.172	.164	.156	.148	.140	.132	.124	.116	.108	.101	.093	.085	.077	.069	.061	.053	.045	.038	.030	0.022	0.014
35.1	.204	.196	.188	.180	.173	.165	.157	.149	.141	.133	.125	.117	.109	.102	.094	.086	.078	.070	.062	.054	.046	.039	.031	.023	.015
35.2	.204	.196	.188	.180	.173	.165	.157	.149	.141	.133	.125	.117	.109	.102	.094	.086	.078	.070	.062	.054	.046	.039	.031	.023	.015
35.3	.205	.197	.189	.181	.174	.166	.158	.150	.142	.134	.126	.118	.110	.103	.095	.087	.079	.071	.063	.055	.047	.040	.032	.024	.016
35.4	.206	.198	.190	.182	.175	.167	.159	.151	.143	.135	.127	.119	.111	.104	.096	.088	.080	.072	.064	.056	.048	.041	.033	.025	.017
35.5	.207	.199	.191	.183	.176	.168	.160	.152	.144	.136	.128	.120	.112	.105	.097	.089	.081	.073	.065	.057	.049	.042	.034	.026	.018
35.6	.208	.200	.192	.184	.177	.169	.161	.153	.145	.137	.129	.121	.113	.106	.098	.090	.082	.074	.066	.058	.050	.043	.035	.027	.019
35.7	.208	.200	.192	.184	.177	.169	.161	.153	.145	.137	.129	.121	.113	.106	.098	.090	.082	.074	.066	.058	.050	.043	.035	.027	.019
35.8	.209	.201	.193	.185	.178	.170	.162	.154	.146	.138	.130	.122	.114	.107	.099	.091	.083	.075	.067	.059	.051	.044	.036	.028	.020
35.9	.210	.202	.194	.186	.179	.171	.163	.155	.147	.139	.131	.123	.115	.108	.100	.092	.084	.076	.068	.060	.052	.045	.037	.029	.021
36.0	.211	.203	.195	.187	.179	.172	.164	.156	.148	.149	.132	.124	.116	.109	.101	.093	.085	.077	.069	.061	.053	.045	.038	.029	.022

TABLE 9.—*Vapor pressure, inches; barometer 21.42 inches; depression of wet bulb (T.—t′), °F*—Continued.

WET BULB 36° TO 40°.

Wet bulb.	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0	21.0	22.0	23.0	24.0
36.0	0.211	0.203	0.195	0.187	0.179	0.172	0.164	0.156	0.148	0.140	0.132	0.124	0.116	0.109	0.101	0.093	0.085	0.077	0.069	0.061	0.053	0.045	0.038	0.029	0.022
36.1	.212	.204	.196	.188	.180	.173	.165	.157	.149	.141	.133	.125	.117	.110	.102	.094	.086	.078	.070	.062	.054	.046	.039	.030	.023
36.2	.213	.205	.197	.189	.181	.174	.166	.158	.150	.142	.134	.126	.118	.111	.103	.095	.087	.079	.071	.063	.055	.047	.040	.031	.024
36.3	.213	.205	.197	.189	.181	.174	.166	.158	.150	.142	.134	.126	.118	.111	.103	.095	.0878	.079	.071	.063	.055	.047	.040	.031	.024
36.4	.214	.206	.198	.190	.182	.175	.167	.159	.151	.143	.135	.127	.119	.112	.104	.096	.088	.080	.072	.064	.056	.048	.041	.032	.025
36.5	.215	.207	.199	.191	.183	.176	.168	.160	.152	.144	.136	.128	.120	.113	.105	.097	.089	.081	.073	.065	.057	.049	.042	.033	.026
36.6	.216	.208	.200	.192	.184	.177	.169	.161	.153	.145	.137	.129	.121	.114	.106	.098	.090	.082	.074	.066	.058	.050	.043	.034	.027
36.7	.217	.209	.201	.193	.185	.178	.170	.162	.154	.146	.138	.130	.122	.114	.106	.098	.090	.082	.074	.066	.058	.050	.043	.035	.027
36.8	.218	.210	.202	.194	.186	.179	.171	.163	.155	.147	.139	.131	.123	.115	.107	.099	.091	.083	.075	.067	.059	.051	.044	.036	.028
36.9	.219	.211	.203	.195	.187	.180	.172	.164	.156	.148	.140	.132	.124	.116	.108	.100	.092	.084	.076	.068	.060	.052	.045	.037	.029
37.0	.219	.211	.203	.195	.187	.180	.172	.164	.156	.148	.140	.132	.124	.116	.109	.101	.093	.085	.077	.069	.061	.053	.046	.038	.030
37.1	.220	.212	.204	.196	.188	.181	.173	.165	.157	.149	.141	.133	.125	.117	.110	.102	.094	.086	.078	.070	.062	.054	.046	.039	.031
37.2	.221	.213	.205	.197	.189	.182	.174	.166	.158	.150	.142	.134	.126	.118	.111	.103	.095	.087	.079	.071	.063	.055	.047	.040	.032
37.3	.222	.214	.206	.198	.190	.183	.175	.167	.159	.151	.143	.135	.127	.119	.112	.104	.096	.088	.080	.072	.064	.056	.048	.041	.033
37.4	.223	.215	.207	.199	.191	.184	.176	.168	.160	.152	.144	.136	.128	.120	.113	.105	.097	.089	.081	.073	.065	.057	.049	.042	.034
37.5	.224	.216	.208	.200	.192	.185	.177	.169	.161	.153	.145	.137	.129	.121	.114	.106	.098	.090	.082	.074	.066	.058	.050	.043	.035
37.6	.225	.217	.209	.201	.193	.186	.178	.170	.162	.154	.146	.138	.130	.122	.115	.107	.099	.091	.083	.075	.067	.059	.051	.044	.036
37.7	.225	.217	.209	.201	.193	.186	.178	.170	.162	.154	.146	.138	.130	.122	.115	.107	.099	.091	.083	.075	.067	.059	.051	.044	.036
37.8	.226	.218	.210	.202	.194	.187	.179	.171	.163	.155	.147	.139	.131	.123	.116	.108	.100	.092	.084	.076	.068	.060	.052	.045	.037
37.9	.227	.219	.211	.203	.195	.188	.180	.172	.164	.156	.148	.140	.132	.124	.117	.109	.101	.093	.085	.077	.069	.061	.053	.046	.038
38.0	.228	.220	.212	.204	.196	.189	.181	.173	.165	.157	.149	.141	.133	.125	.118	.110	.102	.094	.086	.078	.070	.062	.054	.047	.039
38.1	.229	.221	.213	.205	.197	.190	.182	.174	.166	.158	.150	.142	.134	.126	.119	.111	.103	.095	.087	.079	.071	.063	.055	.048	.040
38.2	.230	.222	.214	.206	.198	.191	.183	.175	.167	.159	.151	.143	.135	.127	.120	.112	.104	.096	.088	.080	.072	.064	.056	.049	.041
38.3	.231	.223	.215	.207	.199	.192	.184	.176	.168	.160	.152	.144	.136	.128	.121	.113	.105	.097	.089	.081	.073	.065	.057	.050	.042
38.4	.232	.224	.216	.208	.200	.193	.185	.177	.169	.161	.153	.145	.137	.129	.122	.114	.106	.098	.090	.082	.074	.066	.058	.051	.043
38.5	.233	.225	.217	.209	.201	.194	.186	.178	.170	.162	.154	.146	.138	.130	.123	.115	.107	.099	.091	.083	.075	.067	.059	.052	.044
38.6	.233	.225	.217	.209	.201	.194	.186	.178	.170	.162	.154	.146	.138	.130	.123	.115	.107	.099	.091	.083	.075	.067	.059	.052	.044
38.7	.234	.226	.218	.210	.202	.195	.187	.179	.171	.163	.155	.147	.139	.131	.124	.116	.108	.100	.092	.084	.076	.068	.060	.053	.045
38.8	.235	.227	.219	.211	.203	.196	.188	.180	.172	.164	.156	.148	.140	.132	.125	.117	.109	.101	.093	.085	.077	.069	.061	.054	.046
38.9	.236	.228	.220	.212	.204	.197	.189	.181	.173	.165	.157	.149	.141	.133	.126	.118	.110	.102	.094	.086	.078	.070	.062	.054	.046
39.0	.237	.229	.221	.213	.205	.198	.190	.182	.174	.166	.158	.150	.142	.134	.126	.118	.111	.103	.095	.087	.079	.071	.063	.055	.047
39.1	.238	.230	.222	.214	.206	.199	.191	.183	.175	.167	.159	.151	.143	.135	.127	.119	.112	.104	.096	.088	.080	.072	.064	.056	.048
39.2	.239	.231	.223	.215	.207	.200	.192	.184	.176	.168	.160	.152	.144	.136	.128	.120	.113	.105	.097	.089	.081	.073	.065	.057	.049
39.3	.240	.232	.224	.216	.208	.201	.193	.185	.177	.169	.161	.153	.145	.137	.129	.121	.114	.106	.098	.090	.082	.074	.066	.058	.050
39.4	.241	.233	.225	.217	.209	.202	.194	.186	.178	.170	.162	.154	.146	.138	.130	.122	.115	.107	.099	.091	.083	.075	.067	.059	.051
39.5	.242	.234	.226	.218	.210	.203	.195	.187	.179	.171	.163	.155	.147	.139	.131	.123	.116	.108	.100	.092	.084	.076	.068	.060	.052
39.6	.243	.235	.227	.219	.211	.204	.196	.188	.180	.172	.164	.156	.148	.140	.132	.124	.117	.109	.101	.093	.085	.077	.069	.061	.053
39.7	.244	.236	.228	.220	.212	.205	.197	.189	.181	.173	.165	.157	.149	.141	.133	.125	.118	.110	.102	.094	.086	.078	.070	.062	.054
39.8	.245	.237	.229	.221	.213	.206	.198	.190	.182	.174	.166	.158	.150	.142	.134	.126	.119	.111	.103	.095	.087	.079	.071	.063	.055
39.9	.246	.238	.230	.222	.214	.207	.199	.191	.183	.175	.167	.159	.151	.143	.135	.127	.120	.112	.104	.096	.088	.080	.072	.064	.056
40.0	.247	.239	.231	.223	.215	.207	.200	.192	.184	.176	.168	.160	.152	.144	.136	.128	.121	.113	.105	.097	.089	.081	.073	.065	.057

TABLE 9.—*Vapor pressure, inches; barometer 21.42 inches; depression of wet bulb (T.—t′), °F*—Continued.

WET BULB, 40° TO 44°.

Wet bulb.	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0
40.1	0.247	0.239	0.231	0.223	0.215	0.207	0.200	0.192	0.184	0.176	0.168	0.160	0.152	0.144	0.136	0.128	0.121	0.113
40.2	.248	.240	.232	.224	.216	.208	.201	.193	.185	.177	.169	.161	.153	.145	.137	.129	.122	.114
40.3	.249	.241	.233	.225	.217	.209	.202	.194	.186	.178	.170	.162	.154	.146	.138	.130	.123	.115
40.4	.250	.242	.234	.226	.218	.210	.203	.195	.187	.179	.171	.163	.155	.147	.139	.131	.124	.116
40.5	.251	.243	.235	.227	.219	.211	.204	.196	.188	.180	.172	.164	.156	.148	.140	.132	.125	.117
40.6	.252	.244	.236	.228	.220	.212	.205	.197	.189	.181	.173	.165	.157	.149	.141	.133	.126	.118
40.7	.253	.245	.237	.229	.221	.213	.206	.198	.190	.182	.174	.166	.158	.150	.142	.134	.127	.119
40.8	.254	.246	.238	.230	.222	.214	.207	.199	.191	.183	.175	.167	.159	.151	.143	.135	.128	.120
40.9	.255	.247	.239	.231	.223	.215	.208	.200	.192	.184	.176	.168	.160	.152	.144	.136	.129	.121
41.0	.256	.248	.240	.232	.224	.216	.209	.201	.193	.185	.177	.169	.161	.153	.145	.137	.130	.122
41.1	.257	.249	.241	.233	.225	.217	.210	.202	.194	.186	.178	.170	.162	.154	.146	.138	.131	.123
41.2	.258	.250	.242	.234	.226	.218	.211	.203	.195	.187	.179	.171	.163	.155	.147	.139	.132	.124
41.3	.259	.251	.243	.235	.227	.219	.212	.204	.196	.188	.180	.172	.164	.156	.148	.140	.133	.125
41.4	.260	.252	.244	.236	.228	.220	.213	.205	.197	.189	.181	.173	.165	.157	.149	.141	.134	.126
41.5	.261	.253	.245	.237	.229	.221	.214	.206	.298	.190	.182	.174	.166	.158	.150	.142	.135	.127
41.6	.262	.254	.246	.238	.230	.222	.215	.207	.199	.191	.183	.175	.167	.159	.151	.143	.135	.128
41.7	.263	.255	.247	.239	.231	.223	.216	.208	.200	.192	.184	.176	.168	.160	.152	.144	.136	.129
41.8	.264	.256	.248	.240	.232	.224	.217	.209	.201	.193	.185	.177	.169	.161	.153	.145	.137	.130
41.9	.265	.257	.249	.241	.233	.225	.218	.210	.202	.194	.186	.178	.170	.162	.154	.146	.138	.131
42.0	.266	.258	.250	.242	.234	.226	.219	.211	.203	.195	.187	.179	.171	.163	.155	.147	.139	.132
42.1	.267	.259	.251	.243	.235	.227	.220	.212	.204	.196	.188	.180	.172	.164	.156	.148	.140	.133
42.2	.268	.260	.252	.244	.236	.228	.221	.213	.205	.197	.189	.181	.173	.165	.157	.149	.141	.134
42.3	.269	.261	.253	.245	.237	.229	.222	.214	.206	.198	.190	.182	.174	.166	.158	.150	.142	.135
42.4	.270	.262	.254	.246	.238	.230	.223	.215	.207	.199	.191	.183	.175	.167	.159	.151	.143	.136
42.5	.271	.263	.255	.247	.239	.231	.224	.216	.208	200	.192	.184	.176	.168	.160	.152	.144	.137
42.6	.272	.264	.256	.248	.240	.232	.225	.217	.209	.201	.193	.185	.177	.169	.161	.153	.145	.138
42.7	.273	.265	.257	.249	.241	.233	.226	.218	.210	.202	.194	.186	.178	.170	.162	.154	.146	.139
42.8	.274	.266	.258	.250	.242	.234	.227	.219	.211	.203	.195	.187	.179	.171	.163	.155	.147	.140
42.9	.276	.268	.260	.252	.244	.236	.229	.221	.213	.205	.197	.189	.181	.173	.165	.157	.149	.141
43.0	.277	.269	.261	.253	.245	.237	.230	.222	.214	.206	.198	.190	.182	.174	.166	.158	.150	.142
43.1	.278	.270	.262	.254	.246	.238	.231	.223	.215	.207	.199	.191	.183	.175	.167	.159	.151	.143
43.2	.279	.271	.263	.255	.247	.239	.232	.224	.216	.208	.200	.192	.184	.176	.168	.160	.152	.144
43.3	.280	.272	.264	.256	.248	.240	.233	.225	.217	.209	.201	.193	.185	.177	.169	.161	.153	.145
43.4	.281	.273	.265	.257	.249	.241	.234	.226	.218	.210	.202	.194	.186	.178	.170	.162	.154	.146
43.6	.282	.274	.266	.258	.250	.242	.235	.227	.219	.211	.203	.195	.187	.179	.171	.163	.155	.147
43.6	.283	.275	.267	.259	.251	.243	.235	.228	.220	.212	.204	.196	.188	.180	.172	.164	.156	.148
43.7	.284	.276	.268	.260	.252	.244	.236	.229	.221	.213	.205	.197	.189	.181	.173	.165	.157	.149
43.8	.285	.277	.269	.261	.253	.245	.237	.230	.222	.214	.206	.198	.190	.182	.174	.166	.158	.150
43.9	.286	.278	.270	.262	.254	.246	.238	.231	.223	.215	.207	.199	.191	.183	.175	.167	.159	.151
44.0	.287	.279	.271	.263	.255	.247	.239	.232	.224	.216	.208	.200	.192	.184	.176	.168	.160	.152

TABLE 9.—*Vapor pressure, inches; barometer 21.42 inches; depression of wet bulb (T.—t′), °F*—Continued.

WET BULB, 40° TO 44°.

Wet bulb.	18.0	19.0	20.0	21.0	22.0	23.0	24.0	25.0	26.0	27.0	28.0	29.0	30.0	31.0	32.0	33.0	34.0	35.0	36.0
40.1	0.105	0.097	0.089	0.081	0.073	0.065	0.057	0.049	0.042	0.034	0.026	0.018	0.010	0.002	....	....	....	....	....
40.2	.106	.098	.090	.082	.074	.066	.058	.050	.043	.035	.027	.019	.011	.003	....	....	....	....	....
40.3	.107	.099	.091	.083	.075	.067	.059	.051	.044	.036	.028	.020	.012	.004	....	....	....	....	....
40.4	.108	.100	.092	.084	.076	.068	.060	.052	.045	.037	.029	.021	.013	.005	....	....	....	....	....
40.5	.109	.101	.093	.085	.077	.069	.061	.053	.046	.038	.030	.022	.014	.006	....	....	....	....	....
40.6	.110	.102	.094	.086	.078	.070	.062	.054	.047	.039	.031	.023	.015	.007	....	....	....	....	....
40.7	.111	.103	.095	.087	.079	.071	.063	.055	.048	.040	.032	.024	.016	.008	....	....	....	....	....
40.8	.112	.104	.096	.088	.080	.072	.064	.056	.049	.041	.033	.025	.017	.009	0.001	....	....	....	....
40.9	.113	.105	.097	.089	.081	.073	.065	.057	.050	.042	.034	.026	.018	.010	.002	....	....	....	....
41.0	.114	.106	.098	.090	.082	.074	.066	.058	.050	.043	.035	.027	.019	.011	.003	....	....	....	....
41.1	.115	.107	.099	.091	.083	.075	.067	.059	.051	.044	.036	.028	.020	.012	.004	....	....	....	....
41.2	.116	.108	.100	.092	.084	.076	.068	.060	.052	.045	.037	.029	.021	.013	.005	....	....	....	....
41.3	.117	.109	.101	.093	.085	.077	.069	.061	.053	.046	.038	.030	.022	.014	.006	....	....	....	....
41.1	.118	.110	.102	.094	.086	.078	.070	.062	.054	.047	.039	.031	.023	.015	.007	....	....	....	....
41.5	.119	.111	.103	.095	.087	.079	.071	.063	.055	.048	.040	.032	.024	.016	.008	....	....	....	....
41.6	.120	.112	.104	.096	.088	.080	.072	.064	.056	.048	.041	.033	.025	.017	.009	0.001	....	....	....
41.7	.121	.113	.105	.097	.089	.081	.073	.065	.057	.049	.042	.034	.026	.018	.010	.002	....	....	....
41.8	.122	.114	.106	.098	.090	.082	.074	.066	.058	.050	.043	.035	.027	.019	.011	.003	....	....	....
41.9	.123	.115	.107	.099	.091	.083	.075	.067	.059	.051	.044	.036	.028	.020	.012	.004	....	....	....
42.0	.124	.116	.108	.100	.092	.084	.076	.068	.060	.052	.045	.037	.029	.021	.013	.005	....	....	....
42.1	.125	.117	.109	.101	.093	.085	.077	.069	.061	.053	.046	.038	.030	.022	.014	.006	....	....	....
42.2	.126	.118	.110	.102	.094	.086	.078	.070	.062	.054	.047	.039	.031	.023	.015	.007	....	....	....
42.3	.127	.119	.111	.103	.095	.087	.079	.071	.063	.055	.048	.040	.032	.024	.016	.008	....	....	....
42.4	.128	.120	.112	.104	.096	.088	.080	.072	.064	.056	.049	.041	.033	.025	.017	.009	0.001	....	....
42.5	.129	.121	.113	.105	.097	.089	.081	.073	.065	.057	.050	.042	.034	.026	.018	.010	.002	....	....
42.6	.130	.122	.114	.106	.098	.090	.082	.074	.066	.058	.050	.042	.035	.027	.019	.011	.003	....	....
42.7	.131	.123	.115	.107	.099	.091	.083	.075	.067	.059	.051	.043	.036	.028	.020	.012	.004	....	....
42.8	.132	.124	.116	.108	.100	.092	.084	.076	.068	.060	.052	.044	.037	.029	.021	.013	.005	....	....
42.9	.134	.126	.118	.110	.102	.094	.086	.078	.070	.062	.054	.047	.039	.031	.023	.015	.007	....	....
43.0	.135	.127	.119	.111	.103	.095	.087	.079	.071	.063	.055	.047	.040	.032	.024	.016	.008	....	....
43.1	.136	.128	.120	.112	.104	.096	.088	.080	.072	.064	.056	.048	.041	.033	.025	.017	.009	0.001	....
43.2	.137	.129	.121	.113	.105	.097	.089	.081	.073	.065	.057	.049	.042	.034	.026	.018	.010	.002	....
43.3	.138	.130	.122	.114	.106	.098	.090	.082	.074	.066	.058	.050	.043	.035	.027	.019	.011	.003	....
43.4	.139	.131	.123	.115	.107	.099	.091	.083	.075	.067	.059	.051	.044	.036	.028	.020	.012	.004	....
43.5	.140	.132	.124	.116	.108	.100	.092	.084	.076	.068	.060	.052	.045	.037	.029	.021	.113	.005	....
43.6	.140	.133	.125	.117	.109	.101	.093	.085	.077	.069	.061	.053	.045	.037	.030	.022	.114	.006	....
43.7	.141	.134	.126	.118	.110	.102	.094	.086	.078	.070	.062	.054	.046	.038	.031	.023	.115	.007	....
43.8	.142	.135	.127	.119	.111	.103	.095	.087	.079	.071	.063	.055	.047	.039	.032	.024	.116	.008	....
43.9	.143	.136	.128	.120	.112	.104	.096	.088	.080	.072	.064	.056	.048	.040	.033	.025	.117	.009	0.001
44.0	.144	.137	.129	.121	.113	.105	.097	.089	.081	.073	.065	.057	.049	.041	.034	.026	.118	.010	.002

TABLE 9.—*Vapor pressure, inches; barometer 21.42 inches; depression of wet bulb (T—T'), °F—Continued.*

WET BULB 44° TO 48°.

DEPRESSION OF WET (T—T') FAHR.

Wet bulb.	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0	21.0	22.0	23.0
44.1	0.288	0.280	0.272	0.264	0.256	0.248	0.240	0.233	0.225	0.217	.209	.201	0.193	0.185	0.177	0.169	0.161	0.153	0.115	0.138	0.130	0.122	0.114	0.106
44.2	.289	.281	.273	.265	.257	.249	.241	.234	.226	.218	.210	.202	.194	.186	.178	.170	.162	.154	.146	.139	.131	.123	.115	.107
44.3	.291	.283	.275	.267	.259	.251	.243	.236	.228	.220	.212	.204	.196	.188	.180	.172	.164	.156	.148	.141	.133	.125	.117	.109
44.4	.292	.284	.276	.268	.260	.252	.244	.237	.229	.221	.213	.205	.197	.189	.181	.173	.165	.157	.149	.142	.134	.126	.118	.110
44.5	.293	.285	.277	.289	.261	.253	.245	.238	.230	.222	.214	.206	.198	.190	.182	.174	.166	.158	.150	.143	.135	.127	.119	.111
44.6	.294	.286	.278	.270	.262	.254	.246	.239	.231	.223	.215	.207	.199	.191	.183	.175	.167	.159	.151	.144	.136	.128	.120	.112
44.7	.295	.287	.279	.271	.263	.255	.247	.240	.322	.224	.216	.208	.200	.192	.184	.176	.168	.160	.152	.145	.137	.129	.121	.113
44.8	.296	.288	.280	.272	.264	.256	.248	.241	.233	.225	.217	.209	.201	.193	.185	.177	.169	.161	.153	.146	.138	.130	.122	.114
44.9	.297	.289	.281	.273	.265	.257	.249	.242	.234	.226	.218	.210	.202	.194	.186	.178	.170	.162	.154	.147	.139	.131	.123	.115
45.0	.298	.290	.282	.274	.266	.258	.250	.243	.235	.227	.219	.211	.203	.195	.187	.179	.171	.163	.155	.148	.140	.132	.124	.116
45.1	.300	.292	.284	.276	.268	.260	.252	.244	.237	.229	.221	.213	.205	.197	.189	.181	.173	.165	.157	.149	.141	.133	.125	.118
45.2	.301	.293	.285	.277	.269	.261	.253	.245	.238	.230	.222	.214	.206	.198	.190	.182	.174	.166	.158	.150	.142	.134	.126	.119
45.3	.302	.294	.286	.278	.270	.262	.254	.246	.239	.231	.223	.215	.207	.199	.191	.183	.175	.167	.159	.151	.143	.135	.127	.120
45.4	.303	.295	.287	.279	.271	.263	.255	.247	.240	.232	.224	.216	.208	.200	.192	.184	.176	.168	.160	.152	.144	.136	.128	.121
45.5	.304	.296	.288	.280	.272	.264	.256	.248	.241	.233	.225	.217	.209	.201	.193	.185	.177	.169	.161	.153	.145	.137	.129	.122
45.6	.305	.297	.289	.281	.273	.265	.257	.249	.242	.234	.226	.218	.210	.202	.194	.186	.178	.170	.162	.154	.146	.138	.130	.123
45.7	.306	.298	.290	.282	.274	.266	.258	.250	.243	.235	.227	.219	.211	.203	.195	.187	.179	.171	.163	.155	.147	.139	.131	.124
45.8	.308	.300	.292	.284	.276	.268	.260	.252	.245	.237	.229	.221	.213	.205	.197	.189	.181	.173	.165	.157	.149	.141	.133	.126
45.9	.309	.301	.293	.295	.277	.269	.261	.253	.246	.238	.230	.222	.214	.206	.198	.190	.182	.174	.166	.158	.150	.142	.134	.127
46.0	.310	.302	.294	.286	.278	.270	.262	.254	.247	.239	.231	.223	.215	.207	.199	.191	.183	.175	.167	.159	.151	.143	.135	.128
46.1	.311	.303	.295	.287	.279	.271	.263	.255	.248	.240	.232	.224	.216	.208	.200	.192	.184	.176	.168	.160	.152	.144	.136	.129
46.2	.312	.304	.296	.288	.280	.272	.264	.256	.249	.241	.233	.225	.217	.209	.201	.193	.185	.177	.169	.161	.153	.145	.137	.130
46.3	.313	.305	.297	.289	.281	.273	.265	.257	.250	.242	.234	.226	.218	.210	.202	.194	.186	.178	.170	.162	.154	.146	.138	.131
46.4	.315	.307	.299	.291	.283	.275	.267	.259	.252	.244	.236	.228	.220	.212	.204	.196	.188	.180	.172	.164	.156	.148	.139	.133
46.5	.316	.308	.300	.292	.284	.276	.268	.260	.253	.245	.237	.229	.221	.213	.205	.197	.189	.181	.173	.165	.157	.149	.141	.134
46.6	.317	.309	.301	.293	.285	.277	.269	.261	.254	.246	.238	.230	.222	.214	.206	.198	.190	.182	.174	.166	.158	.150	.142	.134
46.7	.318	.310	.302	.294	.286	.278	.270	.262	.255	.247	.239	.231	.223	.215	.207	.199	.191	.183	.175	.167	.159	.151	.143	.135
46.8	.319	.311	.303	.295	.287	.279	.271	.263	.256	.248	.240	.232	.224	.216	.208	.200	.192	.184	.176	.168	.160	.152	.144	.136
46.9	.321	.313	.305	.297	.289	.281	.273	.265	.258	.250	.242	.234	.226	.218	.210	.202	.194	.186	.178	.170	.162	.154	.146	.138
47.0	.322	.314	.306	.298	.290	.282	.274	.266	.259	.251	.243	.235	.227	.219	.211	.203	.195	.187	.179	.171	.163	.155	.147	.139
47.1	.323	.315	.307	.299	.291	.283	.275	.267	.260	.252	.244	.236	.228	.220	.212	.204	.196	.188	.180	.172	.164	.156	.148	.140
47.2	.324	.316	.308	.300	.292	.284	.276	.268	.261	.253	.245	.237	.229	.221	.213	.205	.197	.189	.181	.173	.165	.157	.149	.141
47.3	.325	.317	.309	.301	.293	.285	.277	.269	.262	.254	.246	.238	.230	.222	.214	.206	.198	.190	.182	.174	.166	.158	.150	.142
47.4	.327	.319	.311	.303	.295	.287	.279	.271	.263	.256	.248	.240	.232	.224	.216	.208	.200	.192	.184	.176	.168	.160	.152	.144
47.5	.328	.320	.312	.304	.296	.288	.280	.272	.264	.257	.249	.241	.233	.225	.217	.209	.201	.193	.185	.177	.169	.161	.153	.145
47.6	.329	.321	.313	.305	.297	.289	.281	.273	.265	.258	.250	.242	.234	.226	.218	.210	.202	.194	.186	.178	.170	.162	.154	.146
47.7	.330	.322	.314	.306	.298	.290	.282	.274	.266	.259	.251	.243	.235	.227	.219	.211	.203	.195	.187	.179	.171	.163	.155	.147
47.8	.332	.324	.316	.308	.300	.292	.284	.276	.268	.261	.253	.245	.237	.229	.221	.213	.205	.197	.189	.181	.173	.165	.157	.149
47.9	.333	.325	.317	.309	.301	.293	.285	.277	.269	.262	.254	.246	.238	.230	.222	.214	.206	.198	.190	.182	.174	.166	.158	.150
48.0	.334	.326	.318	.310	.302	.294	.286	.278	.270	.263	.255	.247	.239	.231	.223	.215	.207	.199	.191	.183	.175	.167	.159	.151

TABLE 9.—*Vapor pressure, inches; barometer 21.42 inches; depression of wet bulb (T.—t′), °F*—Continued.

WET BULB 44.1 TO 50°—Continued.

Wet bulb.	24.0	25.0	26.0	27.0	28.0	29.0	30.0	31.0	32.0	33.0	34.0	35.0	36.0	37.0	38.0	39.0	40.0	41.0	42.0	43.0
44.1	0.098	0.090	0.082	0.074	0.066	0.058	0.050	0.042	0.035	0.027	0.019	0.011	0.003	......	......	......	......	......	......	......
44.2	.099	.091	.083	.075	.067	.059	.051	.043	.036	.028	.020	.012	.004	......	......	......	......	......	......	......
44.3	.101	.093	.085	.077	.069	.061	.053	.045	.038	.030	.022	.014	.006	......	......	......	......	......	......	......
44.4	.102	.094	.086	.078	.070	.062	.054	.046	.039	.031	.023	.015	.007	......	......	......	......	......	......	......
44.5	.103	.095	.087	.079	.071	.063	.055	.047	.040	.032	.024	.016	.008	......	......	......	......	......	......	......
44.6	.104	.096	.088	.080	.072	.064	.056	.048	.040	.032	.025	.017	.009	......	......	......	......	......	......	......
44.7	.105	.097	.089	.081	.073	.065	.057	.049	.041	.033	.026	.018	.010	......	......	......	......	......	......	......
44.8	.106	.098	.090	.082	.074	.066	.058	.050	.042	.034	.027	.019	.011	......	......	......	......	......	......	......
44.9	.107	.099	.091	.083	.075	.067	.059	.051	.043	.035	.028	.020	.012	......	......	......	......	......	......	......
45.0	.108	.100	.092	.084	.076	.068	.060	.052	.044	.036	.029	.021	.013	0.005	......	......	......	......	......	......
45.1	.110	.102	.094	.086	.078	.070	.062	.054	.046	.038	.030	.022	.014	.007	......	......	......	......	......	......
45.2	.111	.103	.095	.087	.079	.071	.063	.055	.047	.039	.031	.023	.015	.008	......	......	......	......	......	......
45.3	.112	.104	.096	.088	.080	.072	.064	.056	.048	.040	.032	.024	.016	.009	......	......	......	......	......	......
45.4	.113	.105	.097	.089	.081	.073	.065	.057	.049	.041	.033	.025	.017	.010	......	......	......	......	......	......
45.5	.114	.106	.098	.090	.082	.074	.066	.058	.050	.042	.034	.026	.018	.011	......	......	......	......	......	......
45.6	.115	.107	.099	.091	.083	.075	.067	.059	.051	.043	.035	.027	.019	.012	......	......	......	......	......	......
45.7	.116	.108	.100	.092	.084	.076	.068	.060	.052	.044	.036	.028	.020	.013	......	......	......	......	......	......
45.8	.118	.110	.102	.094	.086	.078	.080	.062	.054	.046	.038	.029	.021	.015	......	......	......	......	......	......
45.9	.119	.111	.103	.095	.087	.079	.071	.063	.055	.047	.039	.030	.022	.016	......	......	......	......	......	......
46.0	.120	.112	.104	.096	.088	.080	.072	.064	.056	.048	.040	.032	.024	.017	0.009	......	......	......	......	......
46.1	.121	.113	.105	.097	.089	.081	.073	.065	.057	.049	.041	.033	.025	.018	.010	......	......	......	......	......
46.2	.122	.114	.106	.098	.090	.082	.074	.066	.058	.050	.042	.034	.026	.019	.011	......	......	......	......	......
46.3	.123	.115	.107	.099	.091	.083	.075	.067	.059	.051	.043	.035	.027	.020	.012	......	......	......	......	......
46.4	.125	.117	.109	.101	.093	.085	.077	.069	.061	.053	.045	.037	.029	.022	.014	......	......	......	......	......
46.5	.126	.118	.110	.102	.094	.087	.079	.071	.063	.055	.047	.039	.031	.023	.015	......	......	......	......	......
46.6	.127	.119	.111	.103	.095	.088	.080	.072	.064	.056	.048	.040	.032	.024	.016	......	......	......	......	......
46.7	.128	.120	.112	.104	.096	.089	.081	.073	.065	.057	.049	.041	.033	.025	.017	......	......	......	......	......
46.8	.129	.121	.113	.105	.097	.090	.082	.074	.066	.058	.050	.042	.034	.026	.018	......	......	......	......	......
46.9	.131	.123	.115	.107	.099	.091	.083	.075	.067	.059	.051	.043	.035	.027	.019	......	......	......	......	......
47.0	.132	.124	.116	.108	.100	.092	.084	.076	.068	.060	.052	.044	.036	.028	.020	0.012	0.005	......	......	......
47.1	.133	.125	.117	.109	.101	.093	.085	.077	.069	.061	.053	.045	.037	.029	.021	.013	.006	......	......	......
47.2	.134	.126	.118	.110	.102	.093	.086	.078	.070	.062	.054	.046	.038	.030	.022	.014	.007	......	......	......
47.3	.135	.127	.119	.111	.103	.095	.087	.079	.071	.063	.055	.047	.039	.031	.023	.015	.008	......	......	......
47.4	.137	.128	.121	.113	.105	.097	.089	.081	.073	.065	.057	.049	.041	.033	.025	.017	.009	......	......	......
47.5	.138	.129	.122	.114	.106	.098	.090	.082	.074	.066	.058	.050	.042	.034	.026	.018	.010	......	......	......
47.6	.138	.130	.123	.115	.107	.099	.091	.083	.075	.067	.059	.051	.043	.035	.027	.019	.011	......	......	......
47.7	.139	.131	.124	.116	.109	.101	.093	.085	.077	.069	.061	.053	.045	.036	.028	.020	.012	......	......	......
47.8	.141	.133	.126	.118	.110	.102	.094	.086	.078	.070	.062	.054	.046	.038	.030	.022	.014	......	......	......
47.9	.142	.134	.127	.119	.111	.103	.095	.087	.079	.071	.063	.055	.047	.039	.031	.023	.015	......	......	......
48.0	.143	.135	.128	.120	.112	.104	.096	.088	.080	.072	.064	.056	.048	.040	.032	.024	.016	0.008	......	......

TABLE 9.—*Vapor pressure, inches; barometer 21.42 inches; depression of wet bulb (T. –t′), °F*—Continued.

WET BULB 44.1 TO 50°—Continued.

Wet bulb.	24.0	25.0	26.0	27.0	28.0	29.0	30.0	31.0	32.0	23.0	34.0	35.0	36.0	37.0	38.0	39.0	40.0	41.0	42.0	43.0
48.1	....	....	....	....	....	....	....	....	....	....	....	....	....	0.041	0.033	0.025	0.017	0.009	....	....
48.2	....	....	....	....	....	....	....	....	....	....	....	....	....	.043	.035	.027	.019	.011	....	....
48.3	....	....	....	....	....	....	....	....	....	....	....	....	....	.044	.036	.028	.020	.012	....	....
48.4	....	....	....	....	....	....	....	....	....	....	....	....	....	.045	.037	.029	.021	.013	....	....
48.5	....	....	....	....	....	....	....	....	....	....	....	....	....	.046	.038	.030	.022	.014	....	....
48.6	....	....	....	....	....	....	....	....	....	....	....	....	....	.048	.040	.032	.024	.016	....	....
48.7	....	....	....	....	....	....	....	....	....	....	....	....	....	.049	.041	.033	.025	.017	....	....
48.8	....	....	....	....	....	....	....	....	....	....	....	....	....	.050	.042	.034	.026	.018	....	....
48.9	....	....	....	....	....	....	....	....	....	....	....	....	....	.052	.044	.036	.028	.020	....	....
49.0	....	....	....	....	....	....	....	....	....	....	....	....	....	.053	.045	.037	.029	.021	0.013	....
49.1	....	....	....	....	....	....	....	....	....	....	....	....	....	.054	.046	.038	.030	.022	.014	....
49.2	....	....	....	....	....	....	....	....	....	....	....	....	....	.055	.047	.039	.031	.023	.015	....
49.3	....	....	....	....	....	....	....	....	....	....	....	....	....	.057	.049	.041	.033	.025	.017	....
49.4	....	....	....	....	....	....	....	....	....	....	....	....	....	.058	.050	.042	.034	.026	.018	....
49.5	....	....	....	....	....	....	....	....	....	....	....	....	....	.059	.051	.043	.035	.027	.019	....
49.6	....	....	....	....	....	....	....	....	....	....	....	....	....	.061	.053	.045	.037	.029	.021	....
49.7	....	....	....	....	....	....	....	....	....	....	....	....	....	.062	.054	.045	.038	.030	.022	....
49.8	....	....	....	....	....	....	....	....	....	....	....	....	....	.063	.055	.046	.039	.031	.023	....
49.9	....	....	....	....	....	....	....	....	....	....	....	....	....	.065	.057	.048	.041	.033	.025	....
50.0	....	....	....	....	....	....	....	....	....	....	....	....	....	.066	.058	.050	.042	.034	.026	0.018

TABLE 9.—*Vapor pressure, inches; barometer 21.42 inches; depression of wet bulb (T.—t′), °F*—Continued.

WET BULB 48.1° TO 52°.

Wet bulb.	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0
48.1	0.335	0.327	0.319	0.311	0.303	0.295	0.287	0.279	0.271	0.264	0.256	0.248	0.240	0.232	0.224	0.216	0.208	0.200	0.192
48.2	.337	.329	.321	.313	.305	.297	.289	.281	.273	.266	.258	.250	.242	.234	.226	.218	.210	.202	.194
48.3	.338	.330	.322	.314	.306	.298	.290	.282	.274	.267	.259	.251	.243	.235	.227	.219	.211	.203	.195
48.4	.339	.331	.323	.315	.307	.299	.291	.283	.275	.268	.260	.252	.244	.236	.228	.220	.212	.204	.196
48.5	.340	.332	.324	.316	.308	.300	.292	.284	.276	.269	.261	.253	.245	.237	.229	.221	.213	.205	.197
48.6	.342	.334	.326	.318	.310	.302	.294	.286	.278	.271	.263	.255	.247	.239	.231	.223	.215	.207	.199
48.7	.343	.335	.327	.319	.311	.303	.295	.287	.279	.272	.264	.256	.248	.240	.232	.224	.216	.208	.200
48.8	.344	.336	.328	.320	.312	.304	.296	.288	.280	.273	.265	.257	.249	.241	.233	.225	.217	.209	.201
48.9	.345	.337	.329	.321	.314	.306	.298	.290	.282	.274	.266	.258	.250	.242	.235	.226	.218	.210	.202
49.0	.347	.339	.331	.323	.315	.307	.299	.291	.283	.275	.268	.260	.252	.244	.236	.228	.220	.212	.204
49.1	.348	.340	.332	.324	.316	.308	.300	.292	.284	.276	.269	.261	.253	.245	.237	.229	.221	.213	.205
49.2	.349	.341	.333	.325	317	.309	.301	.293	.285	.277	.270	.262	.254	.246	.238	.230	.212	.214	.206
49.3	.351	.343	.335	.327	319	.311	.303	.295	.287	.279	.272	.264	.256	.248	.240	.232	.224	.216	.208
49.4	.352	.344	.336	.328	320	.312	.304	.296	.288	.280	.273	.265	.257	.249	.241	.233	.225	.217	.209
49.5	.353	.345	.337	.329	.321	.313	.305	.297	.289	.281	.274	.266	.258	.250	.242	.234	.226	.218	.210
49.6	.355	.347	.339	.331	.323	.315	.307	.299	.291	.283	.275	.268	.260	.252	.244	.236	.228	.220	.212
49.7	.356	.348	.340	.332	.324	.316	.308	.300	.292	.284	.276	.269	.261	.253	.245	.237	.229	.221	.213
49.8	.357	.349	.341	.333	.325	.317	.309	.301	.293	.285	.277	.270	.262	.254	.246	.238	.230	.222	.214
49.9	.358	.350	.342	.334	.326	.318	.310	.302	.294	.286	.278	.271	.263	.255	.247	.239	.231	.223	.215
50.0	.360	.352	.344	.336	.328	.320	.312	.304	.296	.288	.280	.273	.265	.257	.249	.241	.233	.225	.217
50.1	.361	.353	.345	.337	.329	.321	.313	.305	.297	.289	.281	.274	.266	.258	.250	.242	.234	.226	.218
50.2	.362	.354	.346	.338	.330	.322	.314	.306	.298	.290	.282	.275	.267	.259	.251	.243	.235	.227	.219
50.3	.364	.356	.348	.340	.332	.324	.316	.308	.300	.292	.284	.277	.269	.261	.253	.245	.237	.229	.221
50.4	.365	.357	.349	.341	.333	.325	.317	.309	.301	.293	.285	.278	.270	.262	.254	.246	.238	.230	.222
50.5	.367	.359	.351	.343	.335	.327	.319	.311	.303	.295	.287	.280	.272	.264	.256	.248	.240	.232	.224
50.6	.368	.360	.352	.344	.336	.328	.320	.312	.304	.296	.288	.280	.273	.265	.257	.249	.241	.233	.225
50.7	.369	.361	.353	.345	.337	.329	.321	.313	.305	.297	.289	.281	.274	.266	.258	.250	.242	.234	.226
50.8	.371	.363	.355	.347	.339	.331	.323	.315	.307	.299	.291	.283	.276	.268	.260	.252	.244	.236	.228
50.9	.372	.364	.356	.348	.340	.332	.324	.316	.308	.300	.292	.284	.277	.269	.261	.253	.245	.237	.229
51.0	.373	.365	.357	.349	.341	.333	.325	.317	.309	.301	.293	.285	.278	.270	.262	.254	.246	.238	.230
51.1	.375	.367	.359	.351	.343	.335	.327	.319	.311	.303	.295	.287	.280	.272	.264	.256	.248	.240	.232
51.2	.376	.368	.360	.352	.344	.336	.328	.320	.312	.304	.296	.288	.281	.273	.265	.257	.249	.241	.233
51.3	.377	.369	.361	.353	.345	.337	.329	.321	.313	.305	.297	.289	.282	.274	.266	.258	.250	.242	.234
51.4	.379	.371	.363	.355	.347	.339	.331	.323	.315	.307	.299	.291	.284	.276	.268	.260	.252	.244	.236
51.5	.380	.372	364	.356	.348	.340	.332	.324	.316	.308	.300	.292	.285	.277	.269	.261	.253	.245	.237
51.6	.382	.374	.366	.358	.350	.342	.334	.326	.318	.310	.302	.294	.287	.279	.271	.263	.255	.247	.239
51.7	.383	.375	.367	.359	.351	.343	.335	.327	.319	.311	.303	.295	.288	.280	.272	.264	.256	.248	.240
51.8	.384	.376	368	.360	.352	.344	.336	.328	.320	.312	.304	.296	.289	.281	.273	.265	.257	.249	.241
51.9	.386	.378	370	.362	.354	.346	.338	.330	.322	.314	.306	.298	.291	.283	.275	.267	.259	.251	.243
52.0	.387	.379	371	.363	.355	.347	.339	.331	.323	.315	.307	.299	.292	.284	.276	.268	.260	.252	.244

TABLE 9.—*Vapor pressure, inches; barometer 21.42 inches; depression of wet bulb (T.—t′), °F*—Continued.

WET BULB 48.1° TO 52°—(Continued).

Wet bulb.	19.0	20.0	21.0	22.0	23.0	24.0	25.0	26.0	27.0	28.0	29.0	30.0	31.0	32.0	33.0	34.0	35.0	36.0
48.1	0.184	0.176	0.168	0.160	0.152	0.144	0.136	0.129	0.121	0.113	0.105	0.197	0.089	0.081	0.073	0.065	0.057	0.049
48.2	.186	.178	.170	.162	.154	.146	.138	.131	.123	.115	.107	.099	.091	.083	.075	.067	.059	.051
48.3	.187	.179	.171	.163	.155	.147	.139	.132	.124	.116	.108	.100	.092	.084	.076	.068	.060	.052
48.4	.188	.180	.172	.164	.156	.148	.140	.133	.125	.117	.109	.101	.093	.085	.077	.069	.061	.053
48.5	.189	.181	.173	.165	.157	.149	.141	.134	.126	.118	.110	.102	.094	.086	.078	.070	.062	.054
48.6	.191	.183	.175	.167	.159	.151	.143	.136	.128	.120	.112	.104	.096	.088	.080	.072	.064	.056
48.7	.192	.184	.176	.168	.160	.152	.144	.137	.129	.121	.113	.105	.097	.089	.081	.073	.065	.057
48.8	.193	.185	.177	.169	.161	.153	.145	.138	.130	.122	.114	.106	.098	.090	.082	.074	.066	.058
48.9	.194	.186	.178	.170	.162	.154	.146	.139	.131	.123	.115	.107	.099	.091	.083	.075	.067	.059
49.0	.196	.188	.180	.172	.164	.156	.148	.141	.133	.125	.117	.109	.101	.093	.085	.077	.069	.061
49.1	.197	.189	.181	.173	.165	.157	.149	.142	.134	.126	.118	.110	.102	.094	.086	.078	.070	.062
49.2	.198	.190	.182	.174	.166	.158	.150	.143	.135	.127	.119	.111	.103	.095	.087	.079	.071	.063
49.3	.200	.192	.184	.176	.168	.160	.152	.145	.137	.129	.121	.113	.105	.097	.089	.081	.073	.065
49.4	.201	.193	.185	.177	.169	.161	.153	.146	.138	.130	.122	.114	.106	.098	.090	.082	.074	.066
49.5	.202	.194	.186	.178	.170	.162	.154	.147	.139	.131	.123	.115	.107	.099	.091	.083	.075	.067
49.6	.204	.196	.188	.180	.172	.164	.156	.149	.141	.133	.125	.117	.109	.101	.093	.085	.077	.069
49.7	.205	.197	.189	.181	.173	.165	.157	.150	.142	.134	.126	.118	.110	.102	.094	.086	.078	.070
49.8	.206	.198	.190	.182	.174	.166	.158	.151	.143	.135	.127	.119	.111	.103	.095	.087	.079	.071
49.9	.207	.199	.191	.183	.175	.167	.159	.152	.144	.136	.128	.120	.112	.104	.096	.088	.080	.072
50.0	.209	.201	.193	.185	.177	.169	.161	.153	.145	.137	.129	.121	.114	.106	.098	.090	.082	.074
50.1	.210	.202	.194	.186	.178	.170	.162	.154	.146	.138	.130	.122	.115	.107	.099	.091	.083	.075
50.2	.211	.203	.195	.187	.179	.171	.163	.155	.147	.139	.131	.123	.116	.108	.100	.092	.084	.076
50.3	.213	.205	.197	.189	.181	.173	.165	.157	.149	.141	.133	.125	.118	.110	.102	.094	.086	.078
50.4	.214	.206	.198	.190	.182	.174	.166	.158	.150	.142	.134	.126	.119	.111	.103	.095	.087	.079
50.5	.216	.208	.200	.192	.184	.176	.168	.160	.152	.144	.136	.128	.121	.113	.105	.097	.089	.081
50.6	.217	.209	.201	.193	.185	.177	.169	.161	.153	.145	.137	.129	.121	.114	.106	.098	.090	.082
50.7	.218	.210	.202	.194	.186	.178	.170	.162	.154	.146	.138	.130	.122	.115	.107	.099	.091	.083
50.8	.220	.212	.204	.196	.188	.180	.172	.164	.156	.148	.140	.132	.124	.117	.109	.101	.093	.085
50.9	.221	.213	.205	.197	.189	.181	.173	.165	.157	.149	.141	.133	.125	.118	.109	.101	.094	.086
51.0	.222	.214	.206	.198	.190	.182	.174	.166	.158	.150	.142	.134	.126	.118	.110	.102	.095	.087
51.1	.224	.216	.208	.200	.192	.184	.176	.168	.160	.152	.144	.136	.128	.120	.112	.104	.097	.089
51.2	.225	.217	.209	.201	.193	.185	.177	.169	.161	.153	.145	.137	.129	.121	.113	.105	.098	.090
51.3	.226	.218	.210	.202	.194	.186	.178	.170	.162	.154	.146	.138	.130	.122	.114	.106	.099	.091
51.4	.228	.220	.212	.204	.196	.188	.180	.172	.164	.156	.148	.140	.132	.124	.116	.108	.101	.093
51.5	.229	.221	.213	.205	.197	.189	.181	.173	.165	.157	.149	.141	.133	.125	.117	.109	.102	.094
51.6	.231	.223	.215	.207	.199	.191	.183	.175	.167	.159	.151	.143	.135	.127	.119	.111	.103	.096
51.7	.232	.224	.216	.208	.200	.192	.184	.176	.168	.160	.152	.144	.136	.128	.120	.112	.104	.097
51.8	.233	.225	.217	.209	.201	.193	.185	.177	.169	.161	.153	.145	.137	.129	.121	.113	.105	.098
51.9	.235	.227	.219	.211	.203	.195	.187	.179	.171	.163	.155	.147	.139	.131	.123	.115	.107	.099
52.0	.236	.228	.220	.212	.204	.196	.188	.180	.172	.164	.156	.148	.140	.132	.124	.116	.108	.100

TABLE 9.—*Vapor pressure, inches; barometer 21.42 inches; depression of wet bulb (T.−t′), °F.* Continued.

WET BULB 52.1° TO 56°.

Wet bulb.	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0
52.1	0.389	0.381	0.373	0.365	0.357	0.349	0.341	0.333	0.325	0.317	0.309	0.301	0.294	0.286	0.278	0.270	0.262	0.254	0.246
52.2	.390	.382	.374	.366	.358	.350	.342	.334	.326	.318	.310	.302	.295	.287	.279	.271	.263	.255	.247
52.3	.392	.384	.376	.368	.360	.352	.344	.336	.328	.320	.312	.304	.297	.289	.281	.273	.265	.257	.249
52.4	.393	.385	.377	.369	.361	.353	.345	.337	.329	.321	.313	.305	.298	.290	.282	.274	.266	.258	.250
52.5	.394	.386	.378	.370	.362	.354	.346	.338	.330	.322	.314	.306	.299	.291	.283	.275	.267	.259	.251
52.6	.396	.388	.380	.372	.364	.356	.348	.340	.332	.324	.316	.308	.300	.293	.285	.277	.269	.261	.253
52.7	.397	.389	.381	.373	.365	.357	.349	.341	.333	.325	.317	.309	.301	.294	.286	.278	.270	.262	.254
52.8	.399	.391	.383	.375	.367	.359	.351	.343	.335	.327	.319	.311	.313	.296	.288	.280	.272	.264	.256
52.9	.400	.392	.384	.376	.368	.360	.352	.344	.336	.328	.320	.312	.304	.297	.289	.281	.273	.265	.257
53.0	.402	.394	.386	.378	.370	.362	.354	.346	.338	.330	.322	.314	.306	.298	.291	.283	.275	.267	.259
53.1	.403	.395	.387	.379	.371	.363	.355	.347	.339	.331	.323	.315	.307	.299	.292	.284	.276	.268	.260
53.2	.405	.397	.389	.381	.373	.365	.357	.349	.341	.333	.325	.317	.309	.301	.294	.286	.278	.270	.262
53.3	.406	.398	.390	.382	.374	.366	.358	.350	.342	.334	.326	.318	.310	.302	.295	.287	.279	.271	.263
53.4	.408	.400	.392	.384	.376	.368	.360	.352	.344	.336	.328	.320	.312	.304	.297	.289	.281	.273	.265
53.5	.409	.401	.393	.385	.377	.369	.361	.353	.345	.337	.329	.321	.313	.305	.298	.290	.282	.274	.266
53.6	.411	.403	.395	.387	.379	.371	.363	.355	.347	.339	.331	.323	.315	.307	.299	.292	.284	.276	.268
53.7	.412	.404	.396	.388	.380	.372	.364	.356	.348	.340	.332	.324	.316	.308	.300	.293	.285	.277	.269
53.8	.414	.406	.398	.390	.382	.374	.366	.358	.350	.342	.334	.326	.318	.310	.302	.295	.287	.279	.271
53.9	.415	.407	.399	.391	.383	.375	.367	.359	.351	.343	.335	.327	.319	.311	.303	.296	.288	.280	.272
54.0	.417	.409	.401	.393	.385	.377	.369	.361	.353	.345	.337	.329	.321	.313	.305	.297	.289	.282	.274
54.1	.418	.410	.402	.394	.386	.378	.370	.362	.354	.346	.338	.330	.322	.314	.306	.298	.290	.283	.275
54.2	.420	.412	.404	.396	.388	.380	.372	.364	.356	.348	.340	.332	.324	.316	.308	.300	.292	.285	.277
54.3	.421	.413	.405	.397	.389	.381	.373	.365	.357	.349	.341	.333	.325	.317	.309	.301	.293	.286	.278
54.4	.423	.415	.407	.399	.391	.383	.375	.367	.359	.351	.343	.335	.327	.319	.311	.303	.295	.288	.280
54.5	.424	.416	.408	.400	.392	.384	.376	.368	.360	.352	.344	.336	.328	.320	.312	.304	.296	.289	.281
54.6	.426	.418	.410	.402	.394	.386	.378	.370	.362	.354	.346	.338	.330	.322	.314	.306	.298	.290	.282
54.7	.427	.419	.411	.403	.395	.387	.379	.371	.363	.355	.347	.339	.331	.323	.315	.307	.299	.291	.283
54.8	.429	.421	.413	.405	.397	.389	.381	.373	.365	.357	.349	.341	.333	.325	.317	.309	.301	.293	.285
54.9	.431	.423	.415	.407	.399	.391	.383	.375	.367	.359	.351	.343	.335	.327	.319	.311	.303	.295	.287
55.0	.432	.424	.416	.408	.400	.392	.384	.386	.368	.360	.352	.344	.336	.328	.320	.312	.304	.296	.288
55.1	.434	.426	.418	.410	.402	.394	.386	.378	.370	.362	.354	.346	.338	.330	.322	.314	.306	.298	.290
55.2	.435	.427	.419	.411	.403	.395	.387	.379	.371	.363	.355	.347	.339	.331	.323	.315	.307	.299	.291
55.3	.437	.429	.421	.413	.405	.397	.389	.381	.373	.365	.357	.349	.341	.333	.325	.317	.309	.301	.293
55.4	.438	.430	.422	.414	.406	.398	.390	.382	.374	.366	.358	.350	.342	.334	.326	.318	.310	.302	.294
55.5	.440	.432	.424	.416	.408	.400	.392	.384	.376	.368	.360	.352	.344	.336	.328	.320	.312	.304	.296
55.6	.442	.434	.426	.418	.410	.402	.394	.386	.378	.370	.362	.354	.346	.338	.330	.322	.314	.306	.298
55.7	.443	.435	.427	.419	.411	.403	.395	.387	.379	.371	.363	.355	.347	.339	.331	.323	.315	.307	.299
55.8	.445	.437	.429	.421	.413	.405	.397	.389	.381	.373	.365	.357	.349	.341	.333	.325	.317	.309	.301
55.9	.446	.438	.430	.422	.414	.406	.398	.390	.382	.374	.366	.358	.350	.342	.334	.326	.318	.310	.302
56.0	.448	.440	.432	.424	.416	.408	.400	.392	.384	.376	.368	.360	.352	.344	.336	.328	.320	.312	.304

TABLE 9.—*Vapor pressure, inches; barometer 21.42 inches; depression of wet bulb (T.—t'), °F*—Continued.

WET BULB 52.1° TO 56°—Continued.

Wet bulb.	19.0	20.0	21.0	22.0	23.0	24.0	25.0	26.0	27.0	28.0	29.0	30.0	31.0	32.0	33.0	34.0	35.0	36.0
52.1	0.238	0.230	0.222	0.214	0.206	0.198	0.190	0.182	0.174	0.166	0.158	0.150	0.142	0.134	0.126	0.118	0.110	0.102
52.2	.239	.231	.223	.215	.207	.199	.191	.183	.175	.167	.159	.151	.143	.135	.127	.119	.111	.103
52.3	.241	.233	.225	.217	.209	.201	.193	.185	.177	.169	.161	.153	.145	.137	.129	.121	.113	.105
52.4	.242	.234	.226	.218	.210	.202	.194	.186	.178	.170	.162	.154	.146	.138	.130	.122	.114	.106
52.5	.243	.235	.227	.219	.211	.203	.195	.187	.179	.171	.163	.155	.147	.139	.131	.123	.115	.107
52.6	.245	.237	.229	.221	.213	.205	.197	.189	.181	.173	.165	.157	.149	.141	.133	.125	.117	.109
52.7	.246	.238	.230	.222	.214	.206	.198	.190	.182	.174	.166	.158	.150	.142	.134	.126	.118	.110
52.8	.248	.240	.232	.224	.216	.208	.200	.192	.184	.176	.168	.160	.152	.144	.136	.128	.120	.112
52.9	.249	.241	.233	.225	.217	.209	.201	.193	.185	.177	.169	.161	.153	.145	.137	.129	.121	.113
53.0	.251	.243	.235	.227	.219	.211	.203	.195	.187	.179	.171	.163	.155	.147	.139	.131	.123	.115
53.1	.252	.244	.236	.228	.220	.212	.204	.196	.188	.180	.172	.164	.156	.148	.140	.132	.124	.116
53.2	.254	.246	.238	.230	.222	.214	.206	.198	.190	.182	.174	.166	.158	.150	.142	.134	.126	.118
53.3	.255	.247	.239	.231	.223	.215	.207	.199	.191	.183	.175	.167	.159	.151	.143	.135	.127	.119
53.4	.257	.249	.241	.233	.225	.217	.209	.201	.193	.185	.177	.169	.161	.153	.145	.137	.129	.121
53.5	.258	.250	.242	.234	.226	.218	.210	.202	.194	.186	.178	.170	.162	.154	.146	.138	.130	.122
53.6	.260	.252	.244	.236	.228	.220	.212	.204	.196	.188	.180	.172	.164	.166	.148	.140	.132	.124
53.7	.261	.253	.245	.237	.229	.221	.213	.205	.197	.189	.181	.173	.165	.157	.149	.141	.133	.125
53.8	.263	.255	.247	.239	.231	.223	.215	.207	.199	.191	.183	.175	.167	.159	.151	.143	.135	.127
53.9	.264	.256	.248	.240	.232	.224	.216	.208	.200	.192	.184	.176	.168	.160	.152	.144	.136	.128
54.0	.266	.258	.250	.242	.234	.226	.218	.210	.202	.194	.186	.178	.170	.162	.154	.146	.138	.130
54.1	.267	.259	.251	.243	.235	.227	.219	.211	.203	.195	.187	.179	.171	.163	.155	.147	.139	.131
54.2	.269	.261	.253	.245	.237	.229	.221	.213	.205	.197	.189	.181	.173	.165	.157	.149	.141	.133
54.3	.270	.262	.254	.246	.238	.230	.222	.214	.206	.198	.190	.182	.174	.166	.158	.150	.142	.134
54.4	.272	.264	.256	.248	.240	.232	.224	.216	.208	.200	.192	.184	.176	.168	.160	.152	.144	.136
54.5	.273	.265	.257	.249	.241	.233	.225	.217	.209	.201	.193	.185	.177	.169	.161	.153	.145	.137
54.6	.275	.267	.259	.251	.243	.235	.227	.219	.211	.203	.195	.187	.179	.171	.163	.155	.147	.139
54.7	.276	.268	.260	.252	.245	.237	.228	.220	.212	.204	.196	.188	.180	.172	.164	.156	.148	.140
54.8	.278	.270	.262	.254	.247	.239	.230	.222	.214	.206	.198	.190	.182	.174	.166	.158	.150	.142
54.9	.279	.271	.264	.256	.248	.240	.232	.224	.216	.208	.200	.192	.184	.176	.168	.160	.152	.144
55.0	.280	.272	.265	.257	.249	.241	.233	.225	.217	.209	.201	.193	.185	.177	.169	.161	.153	.145
55.1	.282	.274	.267	.259	.251	.243	......	......	......	......	......	......	......	......	......	......	......	......
55.2	.283	.275	.268	.260	.252	.244	......	......	......	......	......	......	......	......	......	......	......	......
55.3	.285	.277	.270	.262	.254	.246	......	......	......	......	......	......	......	......	......	......	......	......
55.4	.286	.278	.271	.263	.255	.247	......	......	......	......	......	......	......	......	......	......	......	......
55.5	.288	.280	.273	.265	.257	.249	......	......	......	......	......	......	......	......	......	......	......	......
55.6	.290	.282	.274	.266	.258	.250	......	......	......	......	......	......	......	......	......	......	......	......
55.7	.291	.283	.275	.267	.259	.251	......	......	......	......	......	......	......	......	......	......	......	......
55.8	.293	.285	.277	.269	.261	.253	......	......	......	......	......	......	......	......	......	......	......	......
55.9	.294	.286	.278	.270	.262	.254	......	......	......	......	......	......	......	......	......	......	......	......
56.0	.296	.288	.280	.272	.264	.256	......	......	......	......	......	......	......	......	......	......	......	......

TABLE 9.—*Vapor pressure, inches; barometer 21.42 inches; depression of wet bulb (T.—t′), °F*—Continued.

WET BULB 56.1° TO 60°.

Wet bulb.	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0	21.0	22.0	23.0	24.0
56.1	0.450	0.442	0.434	0.426	0.418	0.410	0.402	0.394	0.386	0.378	0.370	0.362	0.354	0.346	0.338	0.330	0.322	0.314	0.306	0.298	0.290	0.282	0.274	0.266	0.258
56.2	.451	.443	.435	.427	.419	.411	.403	.395	.387	.379	.371	.363	.355	.347	.339	.331	.323	.315	.307	.299	.291	.283	.275	.267	.259
56.3	.453	.445	.437	.429	.421	.413	.405	.397	.389	.381	.373	.365	.357	.349	.341	.333	.325	.317	.309	.301	.293	.285	.277	.269	.261
56.4	.455	.447	.439	.431	.423	.415	.407	.399	.391	.383	.375	.367	.359	.351	.343	.335	.327	.319	.311	.303	.295	.287	.279	.271	.263
56.5	.456	.448	.440	.432	.424	.416	.408	.400	.392	.384	.376	.368	.360	.352	.344	.336	.328	.320	.312	.304	.296	.288	.280	.272	.264
56.6	.458	.450	.442	.434	.426	.418	.410	.402	.394	.386	.378	.370	.362	.354	.346	.338	.330	.322	.314	.306	.298	.290	.282	.274	.266
56.7	.460	.452	.444	.436	.428	.420	.412	.404	.396	.388	.380	.372	.364	.356	.348	.340	.332	.324	.316	.308	.300	.292	.284	.276	.268
56.8	.461	.453	.445	.437	.429	.421	.413	.405	.397	.389	.381	.373	.365	.357	.349	.341	.333	.325	.317	.309	.301	.293	.285	.277	.269
56.9	.463	.455	.447	.439	.431	.423	.415	.407	.399	.391	.383	.375	.367	.359	.351	.343	.335	.327	.319	.311	.303	.295	.287	.279	.271
57.0	.465	.457	.449	.441	.433	.425	.417	.409	.401	.393	.385	.377	.369	.361	.353	.345	.337	.329	.321	.313	.305	.297	.289	.281	.273
57.1	.466	.458	.450	.442	.434	.426	.418	.410	.402	.394	.386	.378	.370	.362	.354	.346	.338	.330	.322	.314	.306	.298	.290	.282	.274
57.2	.468	.460	.452	.444	.436	.428	.420	.412	.404	.396	.388	.380	.372	.364	.356	.348	.340	.332	.324	.316	.308	.300	.292	.284	.276
57.3	.470	.462	.454	.446	.438	.430	.422	.414	.406	.398	.390	.382	.374	.366	.358	.350	.342	.334	.326	.318	.310	.302	.294	.286	.278
57.4	.471	.463	.455	.447	.439	.431	.423	.415	.407	.399	.391	.383	.375	.367	.359	.351	.343	.335	.327	.319	.311	.303	.295	.287	.279
57.5	.473	.465	.457	.449	.441	.433	.425	.417	.409	.401	.393	.385	.377	.369	.361	.353	.345	.337	.329	.321	.313	.305	.297	.289	.281
57.6	.475	.467	.459	.451	.443	.435	.427	.419	.411	.403	.395	.387	.379	.371	.363	.355	.347	.339	.331	.323	.315	.307	.299	.291	.283
57.7	.476	.468	.460	.452	.444	.436	.428	.420	.412	.404	.396	.388	.380	.372	.364	.356	.348	.340	.332	.324	.316	.308	.300	.292	.284
57.8	.478	.470	.462	.454	.446	.438	.430	.422	.414	.406	.398	.390	.382	.374	.366	.358	.350	.342	.334	.326	.318	.310	.302	.294	.286
57.9	.480	.472	.464	.456	.448	.440	.432	.424	.416	.408	.400	.392	.384	.376	.368	.360	.352	.344	.336	.328	.320	.312	.304	.296	.288
58.0	.482	.474	.466	.458	.450	.442	.434	.426	.418	.410	.402	.394	.386	.378	.370	.362	.354	.346	.338	.330	.322	.314	.306	.298	.290
58.1	.483	.475	.467	.459	.451	.443	.435	.427	.419	.411	.403	.395	.387	.379	.371	.363	.355	.347	.339	.331	.323	.315	.307	.299	.291
58.2	.485	.477	.469	.461	.453	.445	.437	.429	.421	.413	.405	.397	.389	.381	.373	.365	.357	.349	.341	.333	.325	.317	.309	.301	.293
58.3	.487	.479	.471	.463	.455	.447	.439	.431	.423	.415	.407	.399	.391	.383	.375	.367	.359	.351	.343	.335	.327	.319	.311	.303	.295
58.4	.488	.480	.472	.464	.456	.448	.440	.432	.424	.416	.408	.400	.392	.384	.376	.368	.360	.352	.344	.336	.328	.320	.312	.304	.296
58.5	.490	.482	.474	.466	.458	.450	.442	.434	.426	.418	.410	.402	.394	.386	.378	.370	.362	.354	.346	.338	.330	.322	.314	.306	.298
58.6	.492	.484	.476	.468	.460	.452	.444	.436	.428	.420	.412	.404	.396	.388	.380	.372	.364	.356	.348	.340	.332	.324	.316	.308	.300
58.7	.494	.486	.478	.470	.462	.454	.446	.438	.430	.422	.414	.406	.398	.390	.382	.374	.366	.358	.350	.342	.334	.326	.318	.310	.302
58.8	.495	.487	.479	.471	.463	.455	.447	.439	.431	.423	.415	.407	.399	.391	.383	.375	.367	.359	.351	.343	.335	.327	.319	.311	.303
58.9	.497	.489	.471	.473	.465	.457	.449	.441	.433	.425	.417	.409	.401	.393	.385	.377	.369	.361	.353	.345	.337	.329	.321	.313	.305
59.0	.499	.491	.483	.475	.467	.459	.451	.443	.435	.427	.419	.411	.403	.395	.387	.379	.371	.363	.355	.347	.339	.331	.323	.315	.307
59.1	.501	.493	.485	.477	.469	.461	.453	.445	.437	.429	.421	.413	.405	.397	.389	.381	.373	.365	.357	.349	.341	.333	.325	.317	.309
59.2	.503	.495	.487	.479	.471	.463	.455	.447	.439	.431	.423	.415	.407	.399	.391	.383	.375	.367	.359	.351	.343	.335	.327	.319	.311
59.3	.504	.496	.488	.480	.472	.464	.456	.448	.440	.432	.424	.416	.408	.400	.392	.384	.376	.368	.360	.352	.344	.336	.328	.320	.312
59.4	.506	.598	.490	.482	.474	.466	.458	.450	.442	.434	.426	.418	.410	.402	.394	.386	.378	.370	.362	.354	.346	.338	.330	.322	.314
59.5	.508	.500	.492	.484	.476	.468	.460	.452	.444	.436	.428	.420	.412	.404	.396	.388	.380	.372	.364	.356	.348	.340	.332	.324	.316
59.6	.510	.502	.494	.486	.478	.470	.462	.454	.446	.438	.430	.422	.414	.406	.398	.390	.382	.374	.366	.359	.350	.342	.334	.326	.318
59.7	.512	.504	.496	.488	.480	.472	.464	.456	.448	.440	.432	.424	.416	.408	.400	.392	.384	.376	.368	.360	.352	.344	.336	.328	.320
59.8	.513	.505	.497	.489	.481	.473	.465	.457	.449	.441	.433	.425	.417	.409	.401	.393	.385	.377	.369	.361	.353	.345	.337	.329	.321
59.9	.515	.507	.499	.491	.483	.475	.467	.459	.451	.443	.435	.427	.419	.411	.403	.395	.387	.379	.371	.363	.355	.347	.339	.331	.323
60.0	.517	.509	.501	.493	.485	.477	.469	.461	.453	.445	.437	.429	.421	.413	.405	.397	.389	.381	.373	.365	.357	.349	.341	.333	.325

TABLE 9.—*Vapor pressure, inches; barometer 21.42 inches; depression of wet bulb (T.—t'), °F*—Continued.

WET BULB 60.1° TO 64°.

Wet bulb.	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0	21.0	22.0	23.0	24.0
60.1	0.519	0.511	0.503	0.495	0.487	0.479	0.471	0.463	0.455	0.447	0.439	0.431	0.423	0.415	0.407	0.399	0.391	0.383	0.375	0.367	0.359	0.351	0.343	0.335	0.327
60.2	.521	.513	.505	.497	.489	.481	.473	.465	.457	.449	.441	.433	.425	.417	.409	.401	.393	.385	.377	.369	.361	.353	.345	.337	.329
60.3	.523	.515	.507	.499	.491	.483	.475	.467	.459	.451	.443	.435	.427	.419	.411	.403	.395	.387	.379	.371	.363	.355	.347	.339	.331
60.4	.524	.516	.508	.500	.492	.484	.476	.468	.460	.452	.444	.436	.428	.420	.412	.404	.396	.388	.380	.372	.364	.356	.348	.340	.332
60.5	.526	.518	.510	.502	.494	.486	.478	.470	.462	.454	.446	.438	.430	.422	.414	.406	.398	.390	.382	.374	.366	.358	.350	.342	.334
60.6	.528	.520	.512	.504	.496	.488	.480	.472	.464	.456	.448	.440	.432	.424	.416	.408	.400	.392	.384	.376	.368	.360	.352	.344	.336
60.7	.530	.522	.514	.506	.498	.490	.482	.474	.466	.458	.450	.442	.434	.426	.418	.410	.402	.394	.386	.378	.370	.362	.354	.346	.338
60.8	.532	.524	.516	.508	.500	.492	.484	.476	.468	.460	.452	.444	.436	.428	.420	.412	.404	.396	.388	.380	.372	.364	.356	.348	.340
60.9	.534	.526	.518	.510	.502	.494	.486	.478	.470	.462	.454	.446	.438	.430	.422	.414	.406	.398	.390	.382	.374	.366	.358	.350	.342
61.0	.536	.528	.520	.512	.504	.496	.488	.480	.472	.464	.456	.448	.440	.432	.424	.416	.408	.400	.392	.384	.376	.368	.360	.352	.344
61.1	.538	.530	.522	.514	.506	.498	.490	.482	.474	.466	.458	.450	.442	.434	.426	.418	.410	.402	.394	.386	.378	.370	.362	.354	.346
61.2	.539	.531	.523	.515	.507	.499	.491	.483	.475	.467	.459	.451	.443	.435	.427	.419	.411	.403	.395	.387	.379	.371	.363	.355	.347
61.3	.541	.533	.525	.517	.509	.501	.493	.485	.477	.469	.461	.453	.445	.437	.429	.421	.413	.405	.397	.389	.381	.373	.365	.357	.349
61.4	.543	.535	.527	.519	.511	.503	.495	.487	.479	.471	.463	.455	.447	.439	.431	.423	.415	.407	.399	.391	.383	.375	.367	.359	.351
61.5	.545	.537	.529	.521	.513	.505	.497	.489	.481	.473	.465	.457	.449	.441	.433	.425	.417	.409	.401	.393	.385	.377	.369	.361	.353
61.6	.547	.539	.531	.523	.515	.507	.499	.491	.483	.475	.467	.459	.451	.443	.435	.427	.419	.411	.403	.395	.387	.379	.371	.363	.355
61.7	.549	.541	.533	.525	.517	.509	.501	.493	.485	.477	.469	.461	.453	.445	.437	.429	.421	.413	.405	.397	.389	.381	.373	.365	.357
61.8	.551	.543	.535	.527	.519	.511	.503	.495	.487	.479	.471	.463	.455	.447	.439	.431	.423	.415	.407	.399	.391	.383	.375	.367	.359
61.9	.553	.545	.537	.529	.521	.513	.505	.497	.489	.481	.473	.465	.457	.449	.441	.433	.425	.417	.409	.401	.393	.385	.377	.369	.361
62.0	.555	.547	.539	.531	.523	.515	.507	.499	.491	.483	.475	.467	.459	.451	.443	.435	.427	.419	.411	.403	.395	.387	.379	.371	.363
62.1	.557	.549	.541	.533	.525	.517	.509	.501	.493	.485	.477	.469	.461	.453	.445	.437	.429	.421	.413	.405	.397	.389	.381	.373	.365
62.2	.559	.551	.543	.535	.527	.519	.511	.503	.495	.487	.479	.471	.463	.455	.447	.439	.431	.423	.415	.407	.399	.391	.383	.375	.367
62.3	.561	.553	.545	.537	.529	.521	.513	.505	.497	.489	.481	.473	.465	.457	.449	.441	.433	.425	.417	.409	.401	.393	.385	.377	.369
62.4	.563	.555	.547	.539	.531	.523	.515	.507	.499	.491	.483	.475	.467	.459	.451	.443	.435	.427	.419	.411	.403	.395	.387	.379	.371
62.5	.565	.557	.549	.541	.533	.525	.517	.509	.501	.493	.485	.477	.469	.461	.453	.445	.437	.429	.421	.413	.405	.397	.389	.381	.373
62.6	.567	.559	.551	.543	.535	.527	.519	.511	.503	.495	.487	.479	.471	.463	.455	.447	.439	.431	.423	.415	.407	.399	.391	.383	.375
62.7	.569	.561	.553	.545	.537	.529	.521	.513	.505	.497	.489	.481	.473	.465	.457	.449	.441	.433	.425	.417	.409	.401	.393	.385	.377
62.8	.571	.563	.555	.547	.539	.531	.523	.515	.507	.499	.491	.483	.475	.467	.459	.451	.443	.435	.427	.419	.411	.403	.395	.387	.379
62.9	.573	.565	.557	.549	.541	.533	.525	.517	.509	.501	.493	.485	.477	.469	.461	.453	.445	.437	.429	.421	.413	.405	.397	.389	.381
63.0	.575	.567	.559	.551	.543	.535	.527	.519	.511	.503	.495	.487	.479	.471	.463	.455	.447	.439	.431	.423	.415	.407	.399	.391	.383
63.1	.577	.569	.561	.553	.545	.537	.529	.521	.513	.505	.497	.489	.481	.473	.465	.457	.449	.441	.433	.425	.417	.409	.401	.393	.385
63.2	.579	.571	.563	.555	.547	.539	.531	.523	.515	.507	.499	.491	.483	.475	.467	.459	.451	.443	.435	.427	.419	.411	.403	.395	.397
63.3	.581	.573	.565	.557	.549	.541	.533	.525	.517	.509	.501	.493	.485	.477	.469	.461	.453	.445	.437	.429	.421	.413	.405	.397	.389
63.4	.583	.575	.567	.559	.551	.543	.535	.527	.519	.511	.503	.495	.487	.479	.471	.463	.455	.447	.439	.431	.423	.415	.407	.399	.391
63.5	.585	.577	.569	.561	.553	.545	.537	.529	.521	.513	.505	.497	.489	.481	.473	.465	.457	.449	.441	.433	.425	.417	.409	.401	.393
63.6	.587	.579	.571	.563	.555	.547	.539	.531	.523	.515	.507	.499	.491	.483	.475	.467	.459	.451	.443	.435	.427	.419	.411	.403	.394
63.7	.589	.581	.573	.565	.557	.549	.541	.533	.525	.517	.509	.501	.493	.485	.477	.469	.461	.453	.445	.437	.429	.421	.413	.405	.396
63.8	.591	.583	.575	.567	.559	.551	.543	.535	.527	.519	.511	.503	.495	.487	.479	.471	.463	.455	.447	.439	.431	.423	.415	.407	.398
63.9	.593	.585	.577	.569	.561	.553	.545	.537	.529	.521	.513	.505	.497	.489	.481	.473	.465	.457	.449	.441	.433	.425	.417	.409	.400
64.0	.595	.587	.579	.571	.563	.555	.547	.539	.531	.523	.515	.507	.499	.491	.483	.475	.467	.459	.451	.443	.435	.427	.419	.411	.402

TABLE 9.—*Vapor pressure, inches; barometer 21.42 inches; depression of wet bulb (T.—t′), °F*—Continued.

WET BULB 64.1° TO 55°.

Wet bulb.	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0	21.0	22.0	23.0	24.0
64.1	0.597	0.589	0.581	0.573	0.565	0.558	0.549	0.541	0.533	0.525	0.517	0.509	0.501	0.493	0.485	0.477	0.469	0.461	0.453	0.445	0.437	0.429	0.421	0.413	0.404
64.2	.599	.591	.583	.575	.567	.559	.551	.543	.535	.527	.519	.511	.503	.495	.487	.479	.471	.463	.455	.447	.439	.431	.423	.415	.406
64.3	.601	.593	.585	.577	.569	.561	.553	.545	.537	.529	.521	.513	.505	.497	.489	.481	.473	.465	.457	.449	.441	.433	.425	.417	.408
64.4	.604	.596	.588	.580	.572	.564	.556	.548	.540	.532	.524	.516	.508	.500	.492	.484	.476	.468	.460	.452	.444	.436	.428	.420	.411
64.5	.606	.598	.590	.582	.574	.566	.558	.550	.542	.534	.526	.518	.510	.502	.494	.486	.478	.470	.462	.454	.445	.437	.429	.421	.413
64.6	.608	.600	.592	.584	.576	.568	.560	.552	.544	.536	.528	.520	.512	.504	.496	.488	.480	.472	.464	.456	.447	.439	.431	.423	.415
64.7	.610	.602	.594	.586	.578	.570	.562	.554	.546	.538	.530	.522	.514	.506	.498	.490	.482	.474	.466	.458	.449	.441	.433	.425	.417
64.8	.612	.604	.596	.588	.580	.572	.564	.556	.548	.540	.532	.524	.516	.508	.500	.492	.484	.476	.468	.460	.451	.443	.435	.427	.419
64.9	.614	.606	.598	.590	.582	.574	.566	.558	.550	.542	.534	.526	.518	.510	.502	.494	.486	.478	.470	.462	.453	.445	.437	.429	.421
65.0	.606	.608	.600	.592	.584	.576	.568	.560	.552	.544	.536	.528	.520	.512	.504	.496	.488	.480	.472	.464	.455	.447	.439	.431	.423

APPENDIX B.

TABLE 10.—*Osmotic pressure in atmospheres for depression of the freezing point to 2.999° C.*[1]

	0	1	2	3	4	5	6	7	8	9
0.0	0.000	0.121	0.241	0.362	0.482	0.603	0.724	0.844	0.965	1.085
0.1	1.206	1.327	1.447	1.568	1.688	1.809	1.930	2.050	2.171	2.291
0.2	2.412	2.532	2.652	2.772	2.893	3.014	3.134	3.255	3.375	3.496
0.3	3.616	3.737	3.857	3.978	4.098	4.219	4.339	4.459	4.580	4.700
0.4	4.821	4.941	5.062	5.182	5.302	5.423	5.543	5.664	5.784	5.904
0.5	6.025	6.145	6.266	6.386	6.506	6.628	6.747	6.867	6.988	7.108
0.6	7.229	7.349	7.469	7.590	7.710	7.830	7.951	8.071	8.191	8.312
0.7	8.432	8.552	8.672	8.793	8.913	9.033	9.154	9.274	9.394	9.514
0.8	9.635	9.755	9.875	9.995	10.12	10.24	10.36	10.48	10.60	10.72
0.9	10.84	10.96	11.08	11.20	11.32	11.44	11.56	11.68	11.80	11.92
1.0	12.04	12.16	12.28	12.40	12.52	12.64	12.76	12.88	13.00	13.12
1.1	13.24	13.36	13.48	13.60	13.72	13.84	13.96	14.08	14.20	14.32
1.2	14.44	14.56	14.68	14.80	14.92	15.04	15.16	15.28	15.40	15.52
1.3	15.64	15.76	15.88	16.00	16.12	16.24	16.36	16.48	16.60	16.72
1.4	16.84	16.96	17.08	17.20	17.32	17.44	17.56	17.68	17.80	17.92
1.5	18.04	18.16	18.28	18.40	18.52	18.64	18.76	18.88	19.00	19.12
1.6	19.24	19.36	19.48	19.60	19.72	19.84	19.96	20.08	20.20	20.32
1.7	20.44	20.56	20.68	20.80	20.92	21.04	21.16	21.28	21.40	21.52
1.8	21.64	21.76	21.88	22.00	22.12	22.24	22.36	22.48	22.60	22.72
1.9	22.84	22.96	23.08	23.20	23.32	23.44	23.56	23.68	23.80	23.92
2.0	24.04	24.16	24.23	24.40	24.52	24.63	24.75	24.87	24.99	25.11
2.1	25.23	25.35	25.47	25.59	25.71	25.83	25.95	26.07	26.19	26.31
2.2	26.43	26.55	26.67	26.79	26.91	27.03	27.15	27.27	27.39	27.51
2.3	27.63	27.75	27.87	27.99	28.11	28.23	28.34	28.46	28.58	28.70
2.4	28.82	28.94	29.06	29.18	29.30	29.42	29.54	29.66	29.78	29.90
2.5	30.02	20.14	30.26	30.38	30.50	30.62	30.74	30.86	30.98	31.09
2.6	31.21	31.33	31.45	31.57	31.69	31.81	31.93	32.05	32.17	32.29
2.7	32.41	32.55	32.65	32.77	32.89	33.01	33.13	33.25	33.36	33.48
2.8	33.60	33.72	33.84	33.96	34.08	34.20	34.31	34.43	34.56	34.68
2.9	34.79	34.91	35.04	35.16	35.27	35.39	35.51	35.63	35.75	35.87

[1] Harris, J. A., and Gortner, R. A., Amer. Jour. Botany, 1: 75–78, 1914.

TABLE 11.—*An extension to 5.99° of tables to determine the osmotic pressure of expressed vegetable saps from the depression of the freezing point.*[1]

[Hundredths of degrees, centigrade.]

	0	1	2	3	4	5	6	7	8	9
3.0	35.99	36.11	36.23	36.35	36.47	36.59	36.71	36.83	36.95	37.06
3.1	37.18	37.30	37.42	37.54	37.66	37.78	37.90	38.02	38.14	38.26
3.2	38.38	38.50	38.62	38.73	38.85	38.97	39.09	39.21	39.33	39.45
3.3	39.57	39.69	39.81	39.93	40.05	40.17	40.28	40.40	40.52	40.64
3.4	40.76	40.88	41.00	41.12	41.24	41.36	41.48	41.60	41.71	41.83
3.5	41.95	42.07	42.19	42.31	42.43	42.55	42.67	42.79	42.91	43.02
3.6	43.14	43.26	43.38	43.50	43.62	43.74	32.86	32.98	44.10	44.22
3.7	44.33	44.45	44.57	44.69	44.81	44.93	45.05	45.17	45.29	45.41
3.8	45.52	45.64	45.76	45.88	46.00	46.12	46.24	46.36	46.48	46.60
3.9	46.71	46.83	46.95	47.07	47.19	47.31	47.43	47.55	47.67	47.79
4.0	47.90	48.02	48.14	48.26	48.38	48.50	48.62	48.74	48.86	48.97
4.1	49.09	49.21	49.33	49.45	49.57	49.69	49.81	49.93	50.04	50.16
4.2	50.28	50.40	50.52	50.64	50.76	50.88	50.99	51.11	51.23	51.35
4.3	51.47	51.59	51.71	51.83	51.94	52.06	52.18	52.30	52.42	52.54
4.4	52.66	52.78	52.89	53.01	53.13	53.25	53.37	53.49	53.61	53.73
4.5	53.84	53.96	54.08	54.20	54.32	54.44	54.56	54.68	54.79	54.91
4.6	55.03	55.15	55.27	55.39	55.51	55.62	55.74	55.86	55.98	56.10
4.7	56.22	56.34	56.46	56.57	56.69	56.81	56.93	57.05	57.17	57.29
4.8	57.40	57.52	57.64	57.76	57.88	58.00	58.12	58.23	58.35	58.47
4.9	58.59	58.71	58.83	58.95	59.06	59.18	59.30	59.42	59.54	59.66
5.0	59.78	59.89	60.01	60.13	60.25	60.37	60.49	60.60	60.72	60.84
5.1	60.96	61.08	61.20	61.32	61.43	61.55	61.67	61.79	61.91	62.03
5.2	62.14	62.26	62.38	62.50	62.62	62.74	62.85	62.97	63.09	63.21
5.3	63.33	63.45	63.56	63.68	63.80	63.92	64.04	64.16	64.27	64.39
5.4	64.51	64.63	64.75	64.87	64.98	65.10	65.22	65.34	65.46	65.58
5.5	65.69	65.81	65.93	66.05	66.17	66.29	66.40	66.52	66.64	66.76
5.6	66.88	67.00	67.11	67.23	67.35	67.47	67.59	67.71	67.82	67.94
5.7	68.06	68.18	68.30	68.41	68.53	68.65	68.77	68.89	69.01	69.12
5.8	69.24	69.36	69.48	69.60	69.71	69.83	69.95	70.07	70.19	70.30
5.9	70.42	70.54	70.66	70.78	70.90	71.01	71.13	71.25	71.37	71.49

[1] Harris, J. A., Amer. Jour. of Botany, 2: 418–419, 1915.

APPENDIX C.

STANDARD TITRATION METHODS FOR SOIL ACIDITY AND FOR CARBONATES ("BLACK ALKALI").

The following procedure in titration for the alkalinity and acidity tests is practically that followed by the Bureau of Soils, and a number of soil departments in the agricultural experiment stations:

The equipment required[1] is two 50-cubic centimeter burette titration apparatuses, one 50-cubic centimeter graduate, one 250-cubic centimeter graduate, two 50-cubic centimeter Nesslar tubes, 1-liter flask, four 100-cubic centimeter beakers, two 50-cubic centimeters Royal Berlin porcelain evaporating dishes, one 50-cubic centimeter pipette, two ordinary pipettes or droppers, bottles and jars for reagents, analytical balance, numerous quart jars with screw caps or stoppers, and reagents as indicated by the procedure. The necessary reagents are prepared as follows:

(1.) Standard Potassium hydrogen sulphate solution:

The average single test will not require over 5 cubic centimeters of this solution. Dissolve 5.58 grams of pure $KHSO_4$ in 1 liter of water, and dilute 100 cubic centimeters of this solution to 1 liter. Place the dilute solution in burette jar No. 1, for alkalinity titrations.

(2.) Phenolphthalein indicator:

A drop or two for each alkalinity and acidity test is required. Dissolve 1 gram of phenolphthalein in 100 cubic centimeters of 50 per cent alcohol. Neutralize by adding a few drops of centinormal alkali, until faintly red, then add a drop of centinormal acid, which should remove the color.

(3.) Methyl orange indicator:

A drop or two for each alkalinity test is required. Dissolve 1 gram of methyl orange (indicator) in 1 liter distilled water.

(4.) Normal alkali is prepared by dissolving 39.96 grams of NaOH in 1 liter of water. Since only a few drops of the centinormal solution are needed in preparing the phenolphthalein indicator, and the exact strength is unimportant, use in about the proportion of 0.04 gram per 100 cubic centimeter of water.

(5.) Centinormal acid (HCI):

Exact strength unimportant. About 2 drops in 100 cubic centimeters of water give approximately correct strength.

(6.) Standard sodium hydroxide solution:

Compute quantity required at rate of one-half to 1 cubic centimeter per acidity test made. The solution is not normal, but is computed so that 1 cubic centimeter will have the equivalent value of 4 mg. of calcium. Dissolve 6.4 grams of pure NaOH in 1 liter of freshly boiled distilled water. Place this in burette jar No. 2, for acidity titrations. Exclude air from the jar as far as possible and make-up fresh solution frequently.

(7) Normal potassium nitrate solution:

Use 250 cubic centimeters for each soil examined for acidity. Dissolve 100.93 grams of pure KNO_3 in 1 liter of distilled water.

Alkalinity Test.

Place 100 grams of air-dried soil of the sample to be examined in a quart jar; add 200 cubic centimeters of distilled water; shake occasionally during

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[1] The special equipment required to conduct the work at experiment stations should cost approximately $20 to $25.

12 hours and allow to settle. The test may best be started early in the day, shaking jars occasionally during the day and leaving them to settle overnight. Turbidity of the solution is difficult to eliminate in this test, but time is saved if complete settling occurs.

Draw off with pipette 50 cubic centimeters of the supernatent liquid; filter, if not fairly clear, into an evaporating dish; and evaporate over Bunsen flame, continuing the drying almost to red heat, so that residue is devoid of humus and will cling together in flakes when the dish is scraped. When dish is cool add 50 cubic centimeters of distilled water; allow to stand for two hours; then pour half of solution into each of two 50-cubic centimeter Nesslar tubes. If fusing of residue has been complete, filtering at this stage would be unnecessary, as the flakes of solid matter will remain in evaporating dish.

Add to each Nesslar tube a drop of phenolphthalein indicator, comparing the first tube with that which has not been treated, before treating the second. If the solution in tube 1 is colored pink, carbonate (Na_2CO_3) is present, and the solution is titrated with $KHSO_4$ until pink color disappears. The burette, presumably graduated to tenths of a cubic centimeter, should be estimated to the nearest hundredth just before beginning to titrate, and again as soon as the color disappears. The comparison tube may then be similarly treated, reading the burette for the second treatment, as a check on the first. This second tube is carried simply as a color comparator.

A drop of methyl orange indicator is now added to each of the above tubes, whether or not the titration for carbonate has been made. This will give to each a yellow color, and the second tube will be kept alongside the one which is titrated so that change of color in the latter will be quickly apparent. The titration of the first tube is continued until the slighest reddish or orange tinge appears. This may best be discerned against a white background and not in direct sunlight, which sometimes itself imparts a reddish tinge to the yellowish solution. A final reading of the burette is obtained to compute the quantity of $KHSO_4$ used in titrating for the bicarbonate ($NaHCO_3$).

The amount of the second titration, less the amount of the first, gives the amount necessary to neutralize the HCO_3 originally present, since the first reaction changed the carbonate to bicarbonate, as follows: $Na_2Co_3+KHSO_4=KNaSo_4+NaHCO_3$.

The second titration, or the first if no carbonate was originally present, reduces all bicarbonate present to carbonic acid, as shown by the reaction:

$$NaHCO_3+KHSO_4=KNaSo_4+H_2CO_3.$$

For each 0.01 cubic centimeter of $KHSO_4$ used in the first titration, there was present 0.00246 milligram of CO_3 in the 25 cubic centimeter solution treated, or 0.01968 milligram in the solution representing 100 grams of soil, or 0.00001968 per cent of the soil weight.

For each 0.01 cubic centimeter of $KHSO_4$ in the differential titration, there was present in the original solution 0.0025 mg. of HCO_3 in the 25 cubic centimeter solution used, or 0.02 mg. in the solution representing 100 grams of soil, or 0.00002 per cent of the weight of the soil.

ACIDITY TEST.

Place 100 grams of air-dried soil of the sample to be tested in a quart jar; add 250 cubic centimeters of normal KNO_3 solution and stopper; and shake at intervals of 5 minutes for 3 hours. Let stand overnight. Draw off 125 cubic centimeters of the supernatant liquid, which in this case is usually quite clear; boil 10 minutes to expel carbon dioxide; cool; and add a drop of phenolphthalein indicator. Place the beaker under the burette, against a white background, and titrate with NaOH to the appearance of the faintest pink color.

The amount of the titration being determined by readings of the burette, the amount of acid present in the solution is expressed by the amount of lime which would be required to neutralize it. Each 0.01 cubic centimeter of the sodium hydroxide used in titration is equivalent to 0.04 mg. of calcium carbonate in the 125 cubic centimeter solution used, and while this stands for one-half of the 100 grams of soil treated, it really stands for only two-fifths of the acid in that soil, because the first solution does not completely dissolve the acids. Therefore, each 0.01 cubic centimeter of titration indicates 0.1 mg. of lime necessary to neutralize the 100 grams of soil, or the amount required to neutralize is 0.0001 per cent of soil weight.

In practice, the amount of lime required to neutralize the first foot of soil is expressed in tons per acre, being computed, of course, on a standard or specific weight of soil per acre-foot.

Space is provided on "Summary of Physical and Chemical Properties of Soil" form for tabulating the computed results of alkalinity and acidity tests in terms of percentages of the weight of soil, which are as serviceable for scientific comparisons as any other expression.

LIST OF REFERENCES.

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